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Growth of extensional faults and folds during deposition of an evaporite-dominated half-graben basin; the Carboniferous Billefjorden Trough, Svalbard

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Normal-sense movements along two major strands of the Billefjorden Fault Zone controlled sedimentation in the Carboniferous Billefjorden Trough. The Billefjorden Trough is a more than 2000 meters thick, west-dipping half-graben basin where accommodation was provided by combinations of extensional faulting and folding throughout the basin history. Whereas previous workers have interpreted several of these folds as due to Tertiary contraction, we argue that they developed during rifting, as extensional forced folds in the style described by other workers from rifts such as the Gulf of Suez. The present basin geometry indicates that accommodation was facilitated by a combination of fault relief and fault-related folds such as extensional fault-propagation monoclines, longitudinal rollover folds and a broad syncline that developed in the hanging wall of the master faults. Major fault-tip monoclines with sharp hinges and steep fold-limbs were allowed to develop in the basin as it became dominated by thick sabhka deposits. Some of the monoclines can be traced laterally into intra-basinal half-grabens where we document significant growth of the hanging wall stratigraphy. The basin shows a close link between structural style and the distribution of main facies associations, confirming a tectonic control on the main depositional systems. Three major alluvial fan complexes formed the main fairways for clastic supply into the basin; of which two were associated with relay ramps. The alluvial fan systems mostly kept up with subsidence or prograded far into the basin. This restricted the extent of marine incursions, and resulted in the development of isolated playas. Initial floodplain deposition in the gently subsiding rift-basin centre was followed by marine flooding events localized mainly to the hinges of longitudinal folds and to relay zones. The gently dipping fold flanks caused tidal flats to be developed in lenticular depocentres. As the main segments of the BFZ linked during strain localization, the western basin-margin monocline was likely breached, triggering rapid subsidence with marine flooding and a change to a westward thickening, wedge-shaped depocenter. Subsequently, a gentle relief was gradually re-established in the basin during renewed growth of fault-monoclines. Finally, the entire basin became submerged, with fault-monoclines being reactivated. Causes for this late subsidence include eustacy, thermal relaxation, differential compaction of the basin fill, or faulting driven by regional extension.

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Introduction

Extensional folds within rift-basins have received significant attention in recent years, since their development has been demonstrated to have had a profound effect on footwall uplift and incision, as well as on the characteristics of the hanging wall sedimentary fill (Withjack et al. 1990; Schlische 1995, 1996, Gawthorpe and Leeder, 2000; Sharp et al. 2000; Gawthorpe and Hardy 2002; Khalil and McClay 2002; Jackson et al. 2004). This interest has been motivated by hydrocarbon exploration in subsurface settings, where the details of the basin fill related to the growth of fault-tip folds are often obscured due to limited seismic resolution (e.g., Corfield and Sharp 2000). Contrary to classic models of half-graben systems, dominated by divergent sedimentary wedges in the immediate hanging wall of normal faults, fault-tip folds develop above upward-propagating normal faults and offset the basin depocenter away from the fault. Furthermore, the depocenter may evolve as a longitudinal syncline (Schlische 1996), resulting in lenticular cross-sectional shapes for syntectonic sedimentary units that thin both toward the controlling fault and the hanging wall dipslope (e.g., Sharp et al. 2000). Along-strike, syntectonic deposits will commonly thin towards or onlap onto the flanks of a broad, transverse syncline that forms as a consequence of fault growth, reflecting the displacement gradient along the main, basin-bounding fault zone (e.g. Schlische, 1991, 1996, Gawthorpe & Leeder 2000). In this contribution, we focus on the Carboniferous Billefjorden Trough of Svalbard (Norway). This half-graben basin is dominated by thick sabhka (evaporite) deposits that allowed the development of major fault-tip monoclines with sharp hinges and nearly vertical fold-limbs.

A number of Carboniferous rift-basins on the Barents Shelf (Maher & Welbon, 1989; Braathen et al. 1995; Harland, 1997; Worsley et al. 2001) have received significant attention as exploration targets (Stemmerik and Worsley, 2005). Largely located onshore, the Billefjorden Trough is the best studied of these basins. Excellent exposure allows detailed analysis of the basin evolution and of the interplay between faulting, folding and deposition, subjects that remain enigmatic for similar subsurface plays. The basin includes lacustrine coals and organic-rich evaporites which form potential source rocks as well as siliciclastic and carbonate reservoir units (e.g., Johannessen and Steel, 1992). These studies highlighted the position and temporal development of depocentres in the basin as intimately linked to extensional faulting; views that have been further substantiated by more recent work on the structural evolution of the Billefjorden area (Maher and Braathen, 2011).
The present-day physiography of the Billefjorden Trough includes numerous fjords and valleys that are incised into the basin fill and that offer uniquely exposed sections through the basement, the basin fill and the post-rift cap rocks. In our opinion, the Billefjorden Trough constitutes a world class example of a half-graben basin.

Complimentary data are available from new and previously recorded stratigraphic sections, as well as from coal exploration drill holes. Helicopter- and ground-based Lidar scans have recently been acquired in the study area (Buckley et al., 2008a,b), facilitating detailed 3D photogeological mapping of outcrops and structures, and of vertical as well as lateral changes in stratigraphic architecture. In sum, our new and comprehensive database allows for the first time a detailed analysis of how the growth of extensional faults and associated folds were linked to the evolution of coeval sedimentary basin fills. In our study, we integrate the spatial and temporal evolution of extensional fault-related folds with the development of depositional patterns and architectures at the basin scale. We use evidence for gradual shifts in depositional environments to interpret temporal and spatial modifications in drainage patterns, clastic sediment flux, and changes in accommodation rates.

Regional setting and lithostratigraphy

The Carboniferous Billefjorden Trough is a half-graben basin located in the hanging wall of the steeply

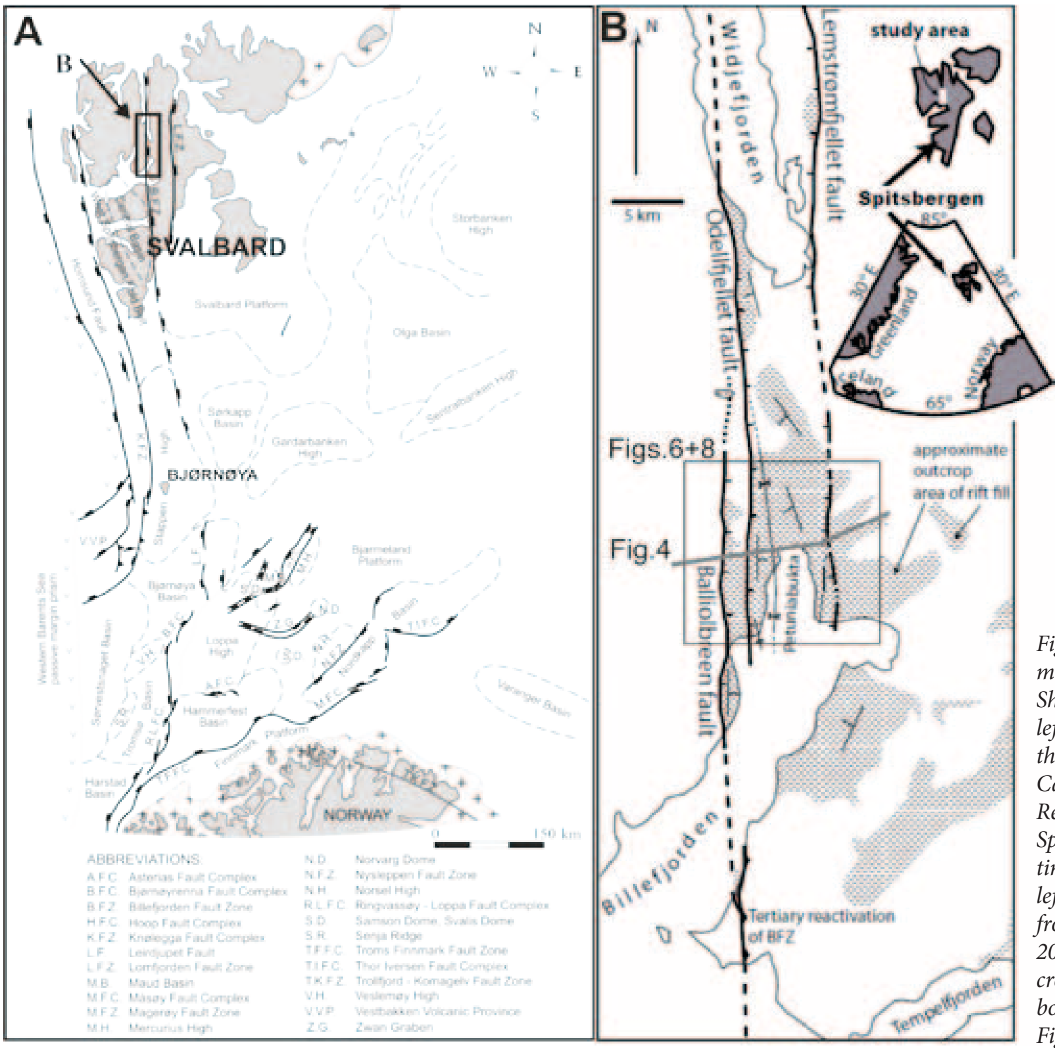

Figure 1. A) Location of major faults on the Barents Shelf, locating the studied Billefjorden Trough. Many of these faults were active during Carboniferous extension. B) Regional map of northeast Spitsbergen (box in A) locating major faults of the Billefjorden Trough (modified from Maher and Braathen, 2010). The line locates the cross-section of Fig. 4 and the box locates the 3D models in Fig. 6 and the map of Fig. 8.

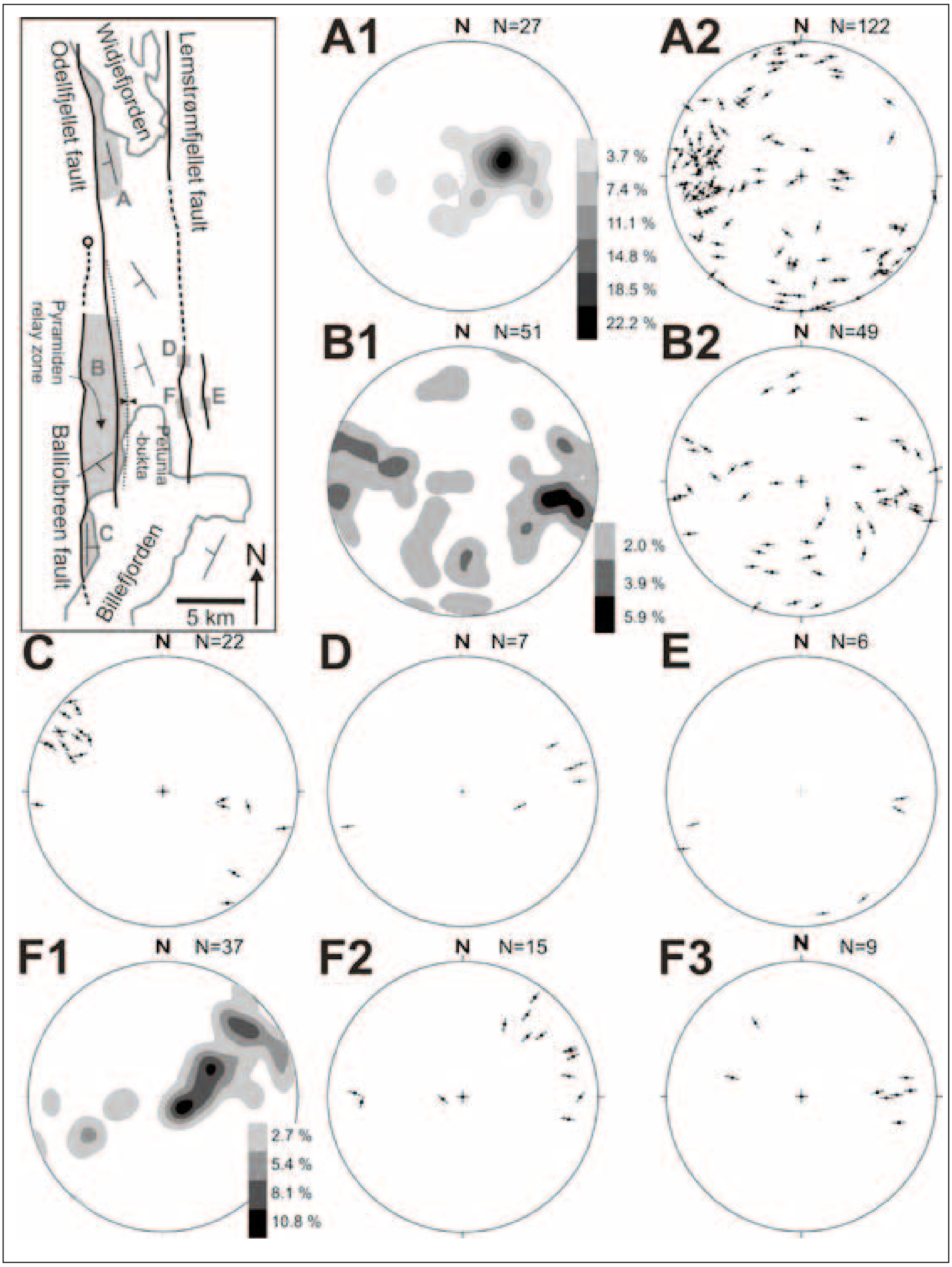

Figure 2. Orientation data for domains A-F, as located on the inset map. Stereo plots are equal area, lower hemisphere. A1) Plot of contoured poles to bedding. A2) Slip-linear plot of slickenside measurements. B1) Plot of contoured poles to bedding. B2) Slip-linear plot of slickenside measurements. C-E) Slip-linear plots of slickenside measurements. F1) Plot of contoured poles to bedding. F2-F3) Slip-linear plots of slickenside measurements. The slip linear plots show the pole to shear fractures and slip-surface of smaller faults recorded in the damage zone of major normal fault segments with syn-rift deposits in the hanging wall. The line or arrow points to the direction of tectonic transport in accordance with the recorded slickenline. See Braathen and Bergh (1995) for plotting method.

east-dipping Billefjorden Fault Zone (BFZ). The basin can be traced from Wijdefjorden in the north to subsurface, seismic expressions in southern Svalbard (Fig. 1) (Bælum and Braathen, in press) over a length of c. 170 km. Because of a gentle, southwards tilt of the regional stratigraphy, the southern part of the basin is now covered by Mesozoic platform deposits, whereas the northernmost part is deeply eroded and partly removed. The Billefjorden area is located between these areas.

Master fault segments of the BFZ dip 60-70° east, and offset the top-basement contact from less than 1000 m in the northern and southern areas to as much as 2000-3000 m around the study area north of Billefjorden. Slickenlines recorded from slip-surfaces around segments of the BFZ show mainly dip-slip, extensional movement on surfaces that parallel the main fault zone (Fig. 2). Some accommodation structures are also present, as would be expected in a damage zone (e.g., Fig. 2, plot A2). Further, rotated and folded bedding display fold axes that are parallel with the master fault segments. In sum, this suggests that overall extensional, dip-slip fault movements on the BFZ and

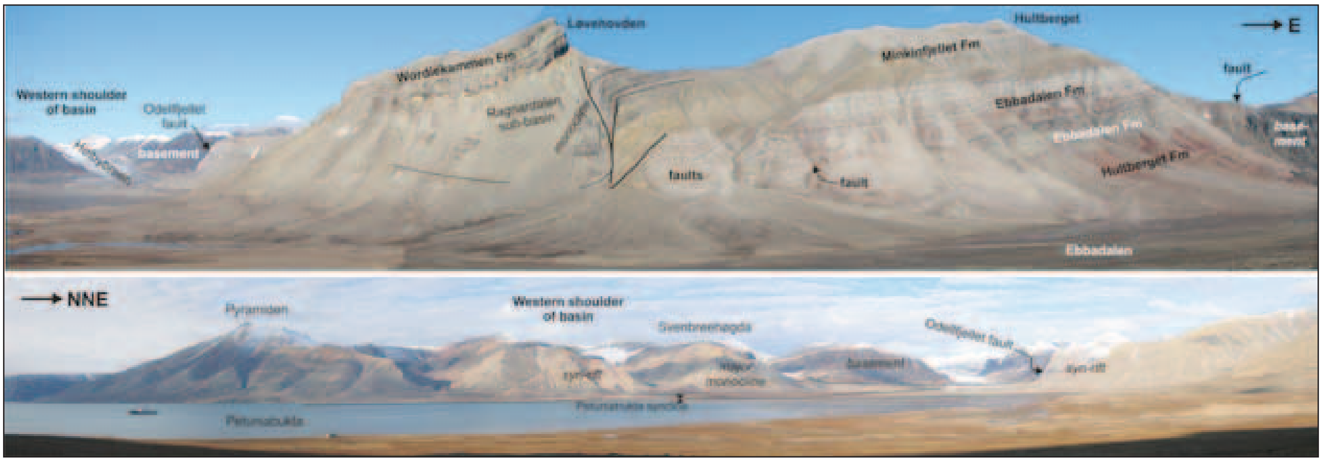

Figure 3. Panoramic photo-mosaics of the Billefjorden Trough, showing basement along the both the western and eastern basin margins, tilted beds dipping towards the basin centre in the WSW, and major faults with associated monoclines. Upper mosaic by A. Braathen; Lower mosaic with courtesy of P.T. Osmundsen.

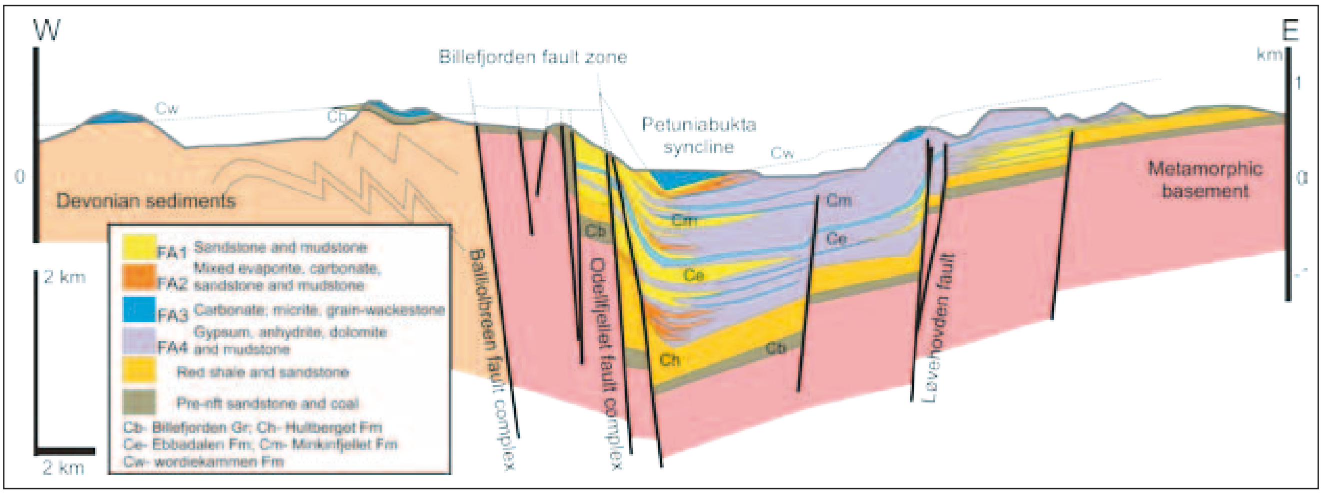

Figure 4. Schematic E-W cross-section of the Billefjorden Trough, outlining the general geometry of the basin with major faults and main stratigraphic units. Lithofacies associations FA1-FA4 are described in the text and in figs. 11 and 12. Note that the maximum syn-rift thickness significantly exceeds the 1200 m indicated in previous publications (see text). See Fig. 1 for location of the section. Note that the vertical and horizontal scales are different.

associated fault segments shaped the Billefjorden Trough. For details around the kinematics of Devonian contractional tectonics west of the BFZ, see Bergh et al. (2011).

The Billefjorden Trough is filled with a mixed succession of siliciclastic, evaporite and carbonate deposits (e.g. Gjelberg & Steel, 1981; Worsley & Aga, 1986: Lønøy, 1995; Pickard et al. 1996; Johannessen and Steel, 2002; Eliassen & Talbot, 2003a, 2005; Maher and Braathen, 2010), with syn-rift deposition dating to Bashkirian and Moscovian times (e.g. Worsley et al. 2001). Some fault activity may have persisted into the Permian (Stemmerik and Worsley, 2005; Maher and Braathen, 2011), attesting to basin development over a period of around 70 mill. years. With a maximum top-basement relief of 4000 meters, this suggests slow fault movement and related subsidence in the range of 7-6 m per 100.000 years. There has been some debate regarding the overall tectonic setting for the Carboniferous rift phase on the Barents Shelf (e.g. Hazeldine 1984; Torsvik et al. 1985; McCann & Dallmann 1996) and, for the Billefjorden Trough, to what extent the basin experienced Tertiary reactivation in the form of contractional deformation (McCann and Dallmann, 1996; Maher and Braathen, 2011). Here, we focus on structures that are associated with thickness variations in the Carboniferous basin fill, thus emphasizing the structural evolution associated with basin formation.

The syn-rift fill of the Billefjorden Trough consists of the Hultberget, Ebbadalen, and Minkinfjellet formations (e.g.,

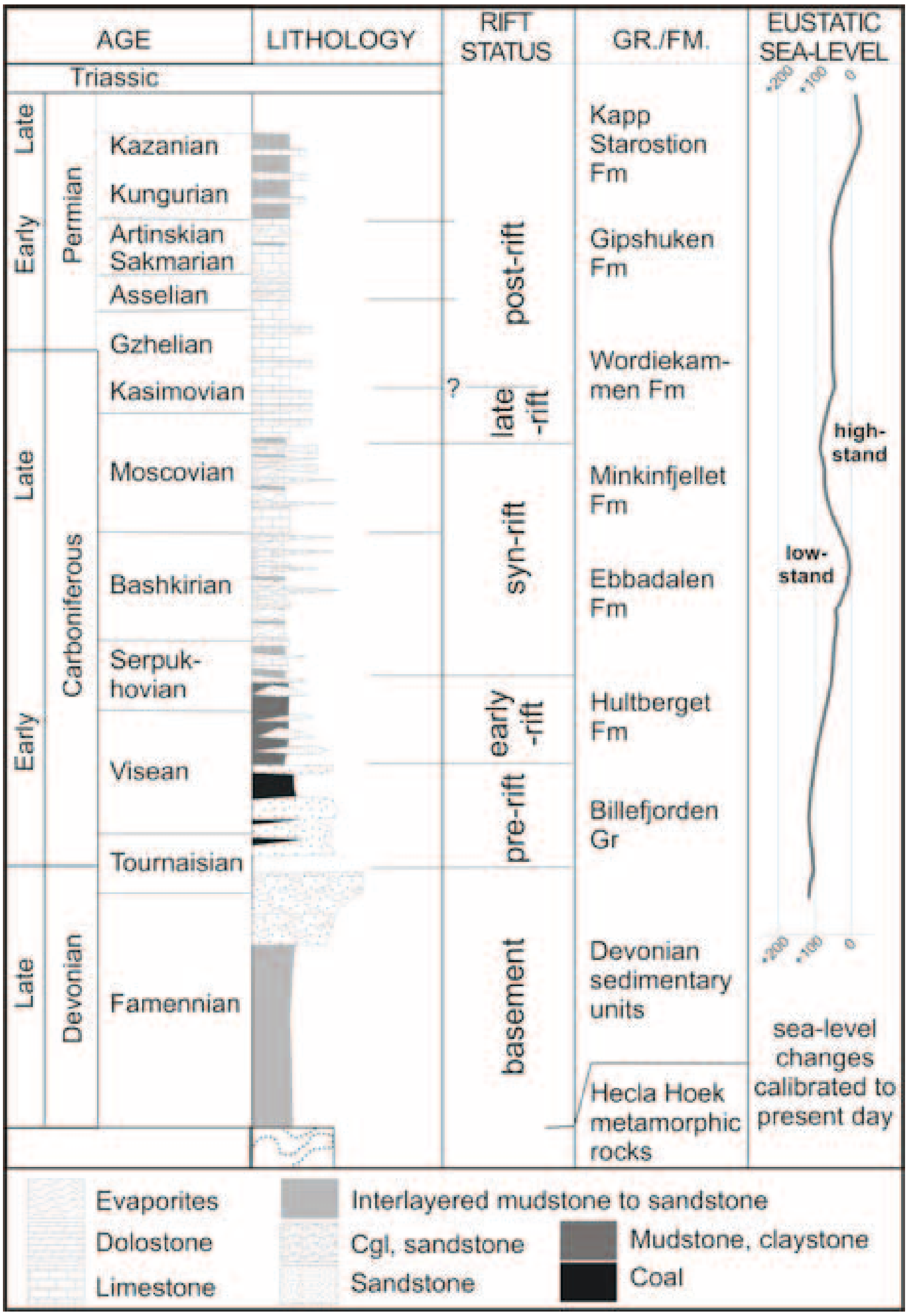

Fig. 5. Schematic lithostratigraphic column with periods, summarized from Dallmann (1999). The first order eustatic sea-level curve is from Haq and Schutter (2008).

Cutbill and Challinor 1965; Dallmann 1999; Johannessen and Steel 1992). The entire rift fill succession is described by the above authors as being approximately 1 km thick, whereas our analysis shows that it is more than 2000 m (see below). In general, the syn-rift units become thicker towards the master fault in the west (towards BFZ), but more complex temporal and spatial relationships are found for individual units in the basin. The half-graben geometry (Figs. 3, 4, 5 and 6) is best expressed by the top of the metamorphic basement rocks (the Hecla Hoek sequence of Harland 1969, 1997), which can be traced underneath the basin. Overlying the basement is a pre-rift succession of fluvial orthoquartzites and coal-shale intervals comprising the Billefjorden Group (Gjellberg and Steel, 1981). To the west of the BFZ, on the Nordfjorden High, deformed Devonian rocks locally underlie either westward-wedging Billefjorden Group strata or strata of the younger Wordiekammen Formation (Fig. 4).

The Billefjorden rift basin fill proper (Dallmann, 1999) commences with the terrestrial red beds of the up to 120 m thick Hultberget Formation. The red beds are interpreted as fluvial channel and coastal plain deposits (Figs. 4, 5 and 7A). Above the Hultberget Formation, the Ebbadalen Formation includes clastic wedges sourced in the Nordfjorden High, that interfinger laterally with evaporate-dominated successions likely to have been deposited in the basin centre (Johannessen and Steel 1992). In more detail, the

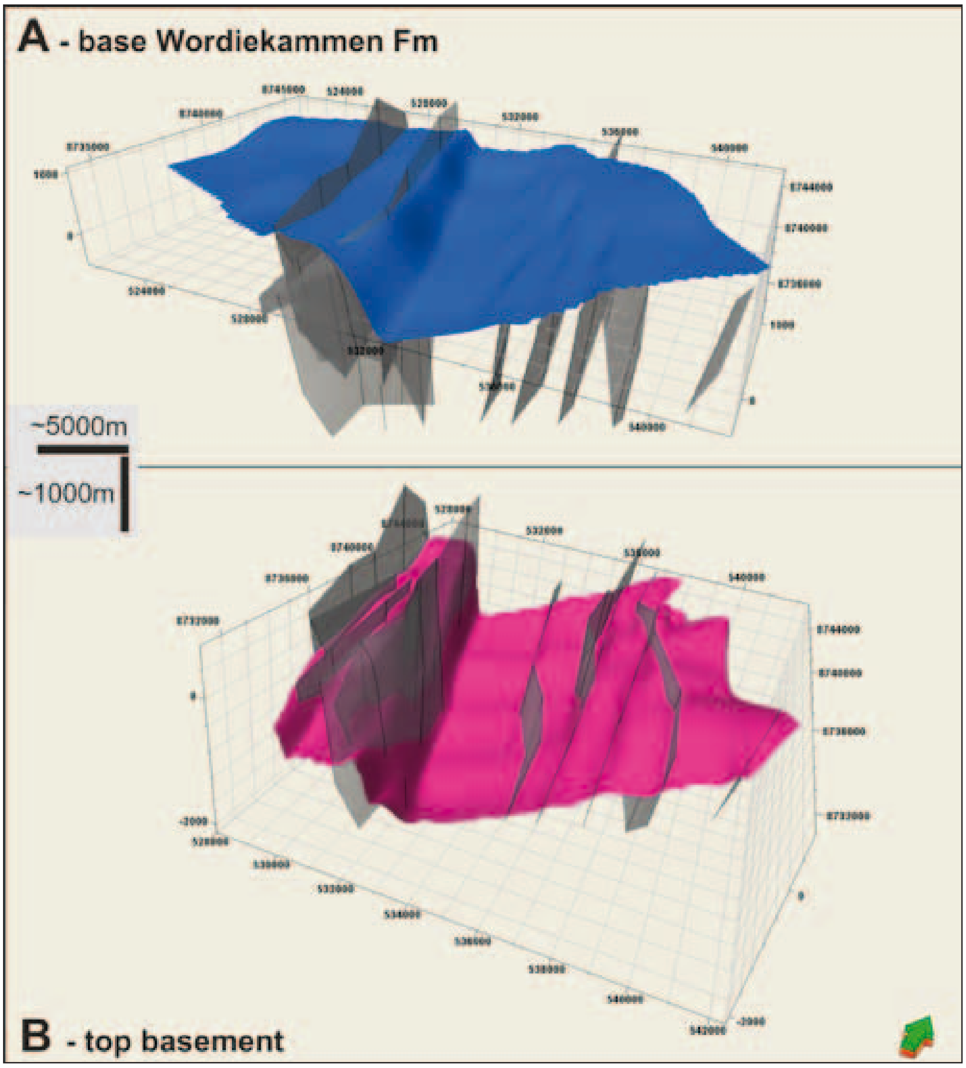

Figure 6. A) Oblique view of a three-dimensional model illustrating the geometry of the base of Wordiekammen Formation, with a post- to late-rift status, and fault segments of the Billefjorden fault zone (BFZ). The regional syncline along the basin axis has been named the Petuniabukta syncline by Maher and Braathen (2011). B) Oblique view of a three-dimensional model showing the top of the metamorphic basement. The latter model is in places constrained by drill holes. Note the geometry of relay zone near Pyramiden. See Fig. 9 for further information around the basin model, and Fig. 10A and E for isochore maps.

Ebbadalen Formation is divided into the lower and thinner Ebbaelva Member, representing tidal and nearshore marine sandstones and shales, and the upper Trikolorfjellet Member, dominated by well-bedded mixed marine carbonates and evaporite sabhka deposits that interfinger with clastic fan deposits towards the west (the latter termed the Odellfjellet Member). On top of the Ebbadalen Formation, the boundary to the overlying Minkinfjellet Formation is defined by the first appearance of a carbonate-dominated succession (Dallmann 1999), which has been associated with a regional basin transgression (Eliassen and Talbot, 2003a; Eliassen and Talbot 2005). Evaporite beds are rare in the lower, micrite-dominated succession whereas stratiform breccias are more common higher up in the Minkinfjellet Formation, in particular on the footwall side of intra-basin faults (Maher and Braathen 2011). Up-section, the Minkinfjellet Formation exhibits carbonates, sandstones, evaporites and breccias (Fig. 7C and D), reflecting significant lateral facies changes in a narrow rift setting, rather similar to the interpreted depositional setting of the Ebbaelva Member (lower Ebbadalen Formation). Depositional dynamics are attributed to active fault margins contributing to temporal and lateral base level changes, which in turn cause recurrent switching from continental, sabhka (tidal flats) to shallow marine deposition. However, the pattern is also assumed to be influenced by upper Carboniferous eustatic sea level changes (Eliassen and Talbot, 2003a,b).

The overlying Wordiekammen Formation has been considered a post-tectonic unit, but Maher and Braathen (2011) document thickness changes across, for example, the N-S-trending Løvehovden fault, which suggests continued fault-controlled basin subsidence. The base of the Wordiekammen Formation is well-defined by a black, cliff- forming micritic carbonate bed, the lowermost of the so-called Black Crag Beds (Pickard et al. 1996; Dallmann 1999). Further up-section the Black Crag Beds are interbedded with thinner, yellow and white wacke- and packstone beds. Locally this succession is cut by breccia pipes formed by karst collapse processes (Eliassen and Talbot, 2003a). Low-angle truncation surfaces observed in the Wordiekammen Formation suggest that the carbonate platform was exposed at times. In line with this

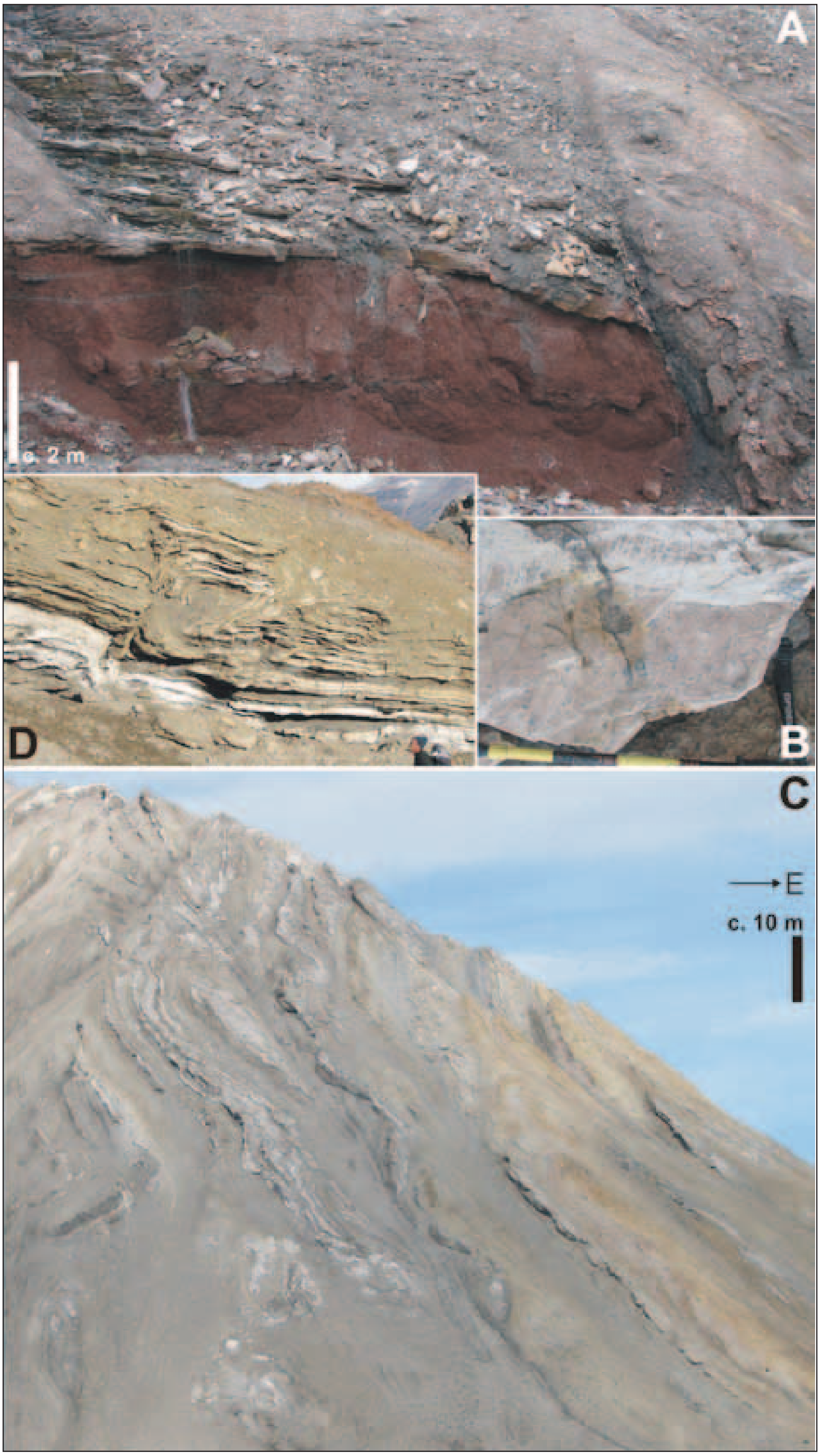

Figure 7. A) Photograph of the contact between the Hultberget Formation flood plain (mainly red mudstone) deposits and the overlying Ebbadalen Formation, with thin-bedded sandstone – mudstone reflecting tidal flat deposits. Note the fault to the right (south), hosting fault parallel mudstone membranes and sandstone lenses in a network of slip surfaces. No deformation bands are developed. The displacement is approximately 45 m. B) Deformation band swarm next to a major fault near Pyramiden, developed in the Ebbadalen Formation red sandstones. Some of these sandstones have significant porosity. C) Photograph of the steep, east-facing fault-tip monocline limb in the hanging wall of the Odellfjellet fault. This steep flank makes up the western limb of the Petuniabukta syncline, with the succession belonging to the upper Minkinfjellet Formation. Note the down-to-the-east (right) shear folds with associated shear zones in the white evaporite, dark shale and black carbonate layers, consistent with down-dip, layer-parallel shear in the steep limb of the monocline, as discussed by Maher and Braathen (2011). Green and yellow layers to the right (east) are sandstones, which are interfingering with evaporites. D) Close-up view of down-limb, down-to-the-east shear folds and shear zones (seen in 'C') in thin-bedded gypsum (white and yellow ledges) and shale (green) layers of the upper Minkinfjellet Formation.

interpretation, Pickard et al. (1996) suggested that a low-relief marine basin centered on the rift continued to exist during deposition of parts of the Wordiekammen Formation.

There are only scattered remnants of the sabhka deposits of the overlying Gipshuken Formation in the study area (Fig. 8), but it is well exposed to the south (Fig. 1). This unit is dominated by carbonates, but contains significant amounts of evaporite, particularly to the south and west.

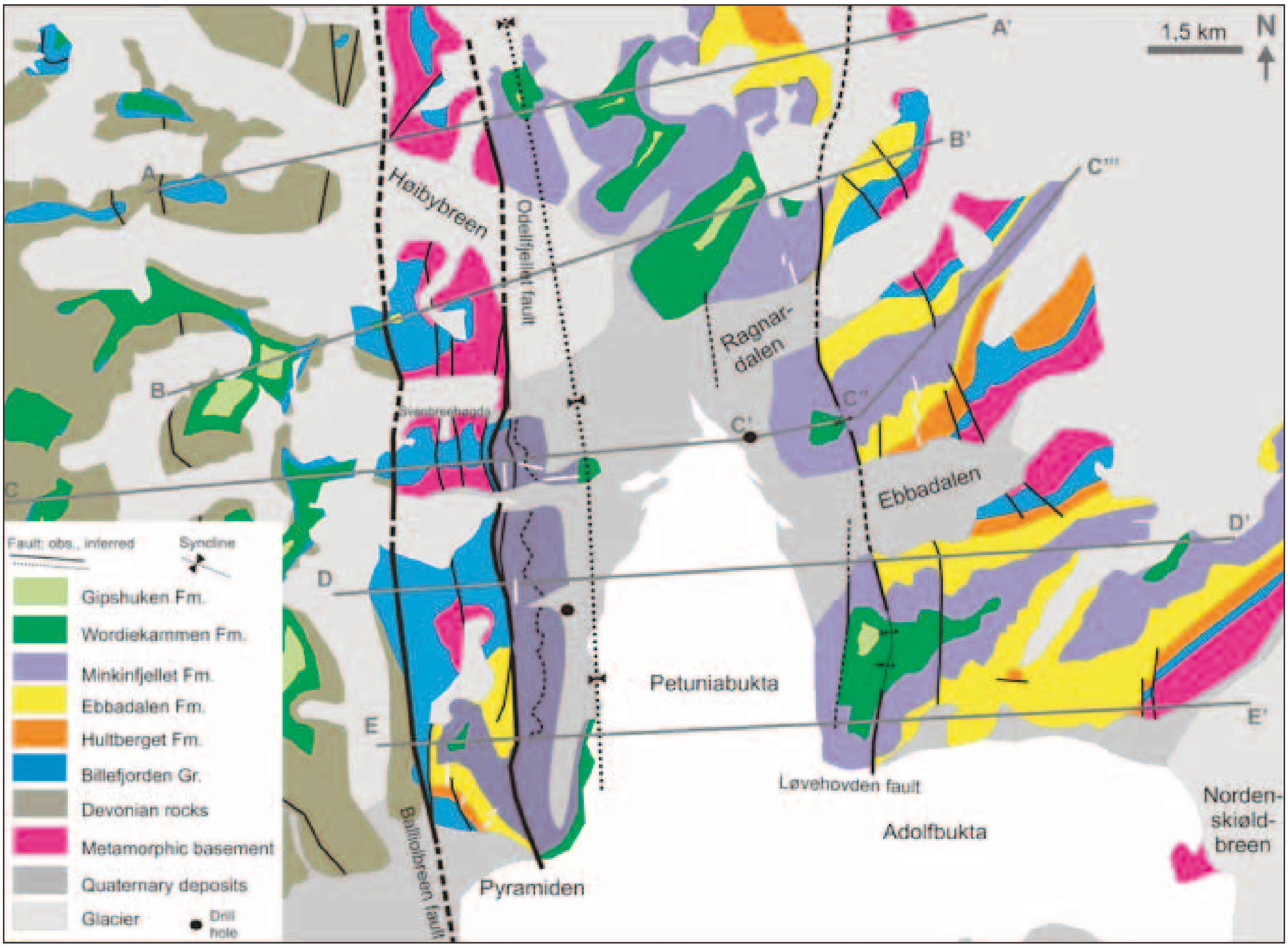

Figure 8. Bedrock map of the Billefjorden Trough (study area shown as box in Fig. 1B), locating the cross-sections of Fig. 9. Logged stratigraphic sections of this work and some published sections (Johannessen and Steel 1992; Eliassen and Talbot 2003a) are located with white lines, whereas the map is modified from Dallmann et al. (2004a,b).

The overlying, open marine Kapp Starostin Formation has a regionally uniform character of silicified shales and carbonates, and entirely post-dates the rift phases.

The work presented here expands on the data presented in Maher and Braathen (2011), which focused on the characteristics of the Løvehovden fault and its hanging wall sub-basin, located just east of the main axis of the Billefjorden Trough. Their main conclusion was that the debated monocline along parts of this fault is a Carboniferous extensional structure, as opposed to previous models involving Tertiary folding and thrusting. Footwall exhumation with erosion and a syn-rift hanging wall sub-basin corroborate this interpretation. For details around the tectonics of the Devonian basin west of the study area, the reader is referred to Bergh et al. (2011). Further, the along-strike characteristics of the Billefjorden Trough and BFZ to the south of the study area, as seen in seismic reflection data, are discussed in Bælum and Braathen (in press).

Fault growth and interaction

The Billefjorden Trough changes its geometry along strike. In the north, the Lemstrømfjellet and Odellfjellet faults (Fig. 1B) bound what appears as a fairly symmetrical graben. Southwards, in Billefjorden, the basin is asymmetrical, with most of the displacement accommodated along segments of the BFZ, thus forming the master fault zone. On a more detailed scale, there are more complex geometries caused by displacement transfer between the Odellfjellet and Balliolbreen segments of the BFZ (Figs. 8, 9 and 10). Furthermore, the southern extent of the Lemstrømfjellet fault zone, the Løvehovden fault (Maher and Braathen, 2011), shows changes in fault offset through the area.

In the northern parts of the study area (Fig. 8), the BFZ consists of two well- defined fault segments, the Odellfjellet and Balliolbreen faults. They are seen as N-S striking, steeply east-dipping (60-70°) master faults bounding a basement-cored block (Fig. 9, section A-A'). The western fault, the Balliolbreen fault, juxtaposes metamorphic basement of the hanging wall (in the block) with Devonian

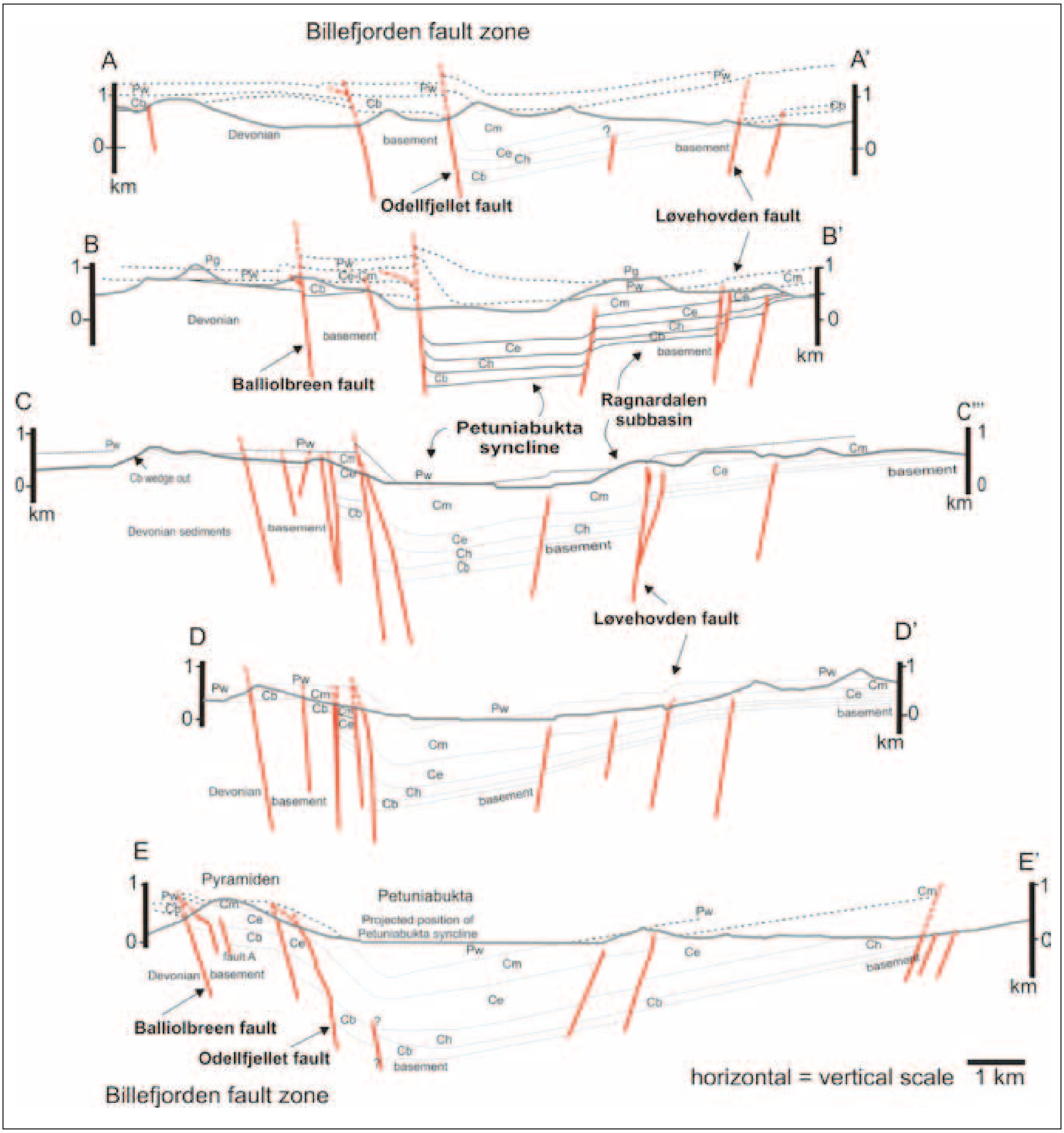

Figure 9. E-W cross-sections of the Billefjorden Trough. Datasets incorporated in the sections include information from mountain sides partly projected into the sections, including surfaces derived from Lidar scan data, and some drill holes in the area (some located on map in Fig. 8). For section construction in the valley and bay areas (e.g., Petuniabukta), down-plunge projection of contacts according to the general dip of beds and the mapped hinge of the Petuniabukta syncline (see Maher and Braathen, 2011) has been used as a reference frame. For the syn-rift succession, thicknesses across faults are assumed to increase in accordance with documented displacement gradients. Note that deeper parts of the basin (below Petuniabukta) are poorly constrained.

sedimentary rocks in the footwall, consistent with a major reverse fault of presumed latest Devonian age (Bergh et al., 2011). There are also indications of probable Tertiary reverse reactivation of this fault, as suggested by an up to 70 m reverse offset of the Permian Wordiekammen Formation, as shown in cross-sections A, B and C (Fig. 9). In the same area, this unit also hosts a low-angle reverse splay fault which cuts into the footwall. The eastern margin of the basement block is distinctly different. This boundary is defined by the Odellfjellet fault, which is a normal fault with more than 1000 m down-to-the-east offset of the metamorphic basement. Characteristically for this fault, the hanging wall rift succession is folded into a syncline with a narrow hinge, which can be traced throughout the study area, with bedding in the proximal hanging wall at many places nearly paralleling the steeply dipping fault (Fig. 7C). The synclinal hinge of this monocline has been named the Petuniabukta syncline (Maher and Braathen, 2011).

As part of a transfer zone to the west of the Odellfjellet fault, NNE-SSW striking fault segments connect to its footwall, most of which have normal, down-to-the-SE offset (Figs. 8 and 9, sections B, C and D). Detailed mapping of these faults reveals significant variation in fault displacement, as shown by gentle-to-moderate SE dips of various contacts and a significant top-basement relief. In the south (Fig. 9, section E), the NNE-SSW striking fault segments in the footwall of the Odellfjellet fault connect to the Balliolbreen fault, the latter exhibiting a different character than in the north. Albeit still preserving the overall reverse offset of the basement on top of Devonian rocks, the Balliolbreen fault has an additional down-to-the-east throw of 200-300 m of the Early Carboniferous, pre-rift Billefjorden Group succession in the hanging wall, consistent with normal reactivation of the major, Latest Devonian reverse fault. This normal offset is also supported by the characteristics of the Ebbadalen Formation syn-rift deposits (see below), which further constrain the timing of extensional faulting to the Carboniferous. In the transfer zone the top of the basement in the hanging wall, as well as bedding in the overlying syn-rift succession, dip 15-20 degrees to the SE; oblique to both the Balliolbreen and Odellfjellet faults. This attests to significant displacement gradients on the faults, especially on the Balliolbreen fault, and is a diagnostic signature of relay zones (e.g., Fossen et al. 2010). In the same area, the Odellfjellet fault breaches the eastern limb of an open anticline, with the gently south-plunging Petuniabukta syncline located in the hanging wall. These folds make up a major monocline. Stratigraphic offset of the Minkinfjellet Formation across the fault is around 200-300 m; however, the base of the Wordiekammen Formation shows a total relief of nearly 1200 m (Fig. 6A). This offset probably diminishes southwards where the Balliolbreen fault replaces the Odellfjellet fault as the master fault segment of the BFZ (Fig. 1B). On a detailed scale, the studied faults are locally associated with damage zones in sandstone characterized by cataclastic deformation bands, attesting to significant porosity during faulting (e.g., Fossen et al. 2007). In contrast, both joints and shear fractures are encountered in carbonates, and cm-dm wide, plastic shear zones are seen in evaporites (Fig. 7) (Maher and Braathen 2011).

In summary, the displacement gradients depicted for the Odellfjellet and Balliolbreen faults, and the connecting fault splays, suggest that there is an overall relay zone between the Odellfjellet and Balliolbreen fault strands in the Billefjorden area. This relay zone transferred displacement from the Odellfjellet master fault in the north to a similarly dominant Balliolbreen master fault southwards.

Faulting in the eastern part of the basin reflects the diminishing displacement along the regional Lemstrømfjellet fault zone (Maher and Braathen, 2011). There, the general gentle western dip of the basin succession towards the BFZ is disrupted by several west-dipping normal faults, some with associated monoclines or drag-folds (Figs. 8 and 9, sections B, C and D). The easternmost fault shows around 200 m down-to-the-west offset of the basement and overlying pre-rift succession, but appears to terminate rapidly up-section in the syn-rift deposits. This fault could have been activated during deposition of the Hultberget Formation, and developed its main offset during deposition of the lower parts of the Ebbadalen Formation. A similar evolution is envisaged for the next fault to the west, just east of the Løvehovden fault. This fault has a characteristic curved geometry up-section, becoming vertical before terminating in the Ebbadalen Formation. The western hanging wall shows a narrow, monocline-like fold in evaporites (Fig. 3). The next fault to the west is the Løvehovden fault (Maher and Braathen, 2011), with its sub-basin of Minkinfjellet Formation age in the western hanging wall. These authors document footwall uplift of the footwall block to the Løvehovden fault. Exhumation and erosion of this block is expressed by a truncative contact that cut down-section towards the Løvehovden fault, and associated exhumational breccia layers above the erosional surface. There is also a paleo-valley at the same stratigraphic level farther east along the eastern sub-basinal margin. The hanging wall sub-basin deepens southwards from around 200 m in Ragnardalen to more than 250 m in the Ebbadalen area. Furthermore, a sharp fault trace on the north slopes of Ragnardalen is replaced southwards by a major monocline in Ebbadalen, showing narrow fold hinges and a vertical limb that parallels the underlying fault (Fig. 3). Maher and Braathen (2011) also present evidence for renewed activity on the Løvehovden fault during the lower Wordiekammen Formation deposition. The lower succession of this unit reveals onlapping beds onto a fault-tip fold. On the other hand, it is questionable if the fault accommodated movements that pre-dated the Minkinfjellet Formation, since the subsurface geometry of the fault and sub-basin, as constrained by a drill hole in the hanging wall (Fig. 9, section C), leaves limited room for increasing the thickness of the Ebbadalen Formation.

Another fault occurs west of the Løvehovden fault, expressed as a monocline in evaporites below the Wordiekammen Formation. Little is known about this fault since available outcrops only show the fault tip. This likely reflects the fact that all the faults in the central parts of the Billefjorden Trough are buried under the late-rift succession, particularly southwards; hence, their displacement is unconstrained.

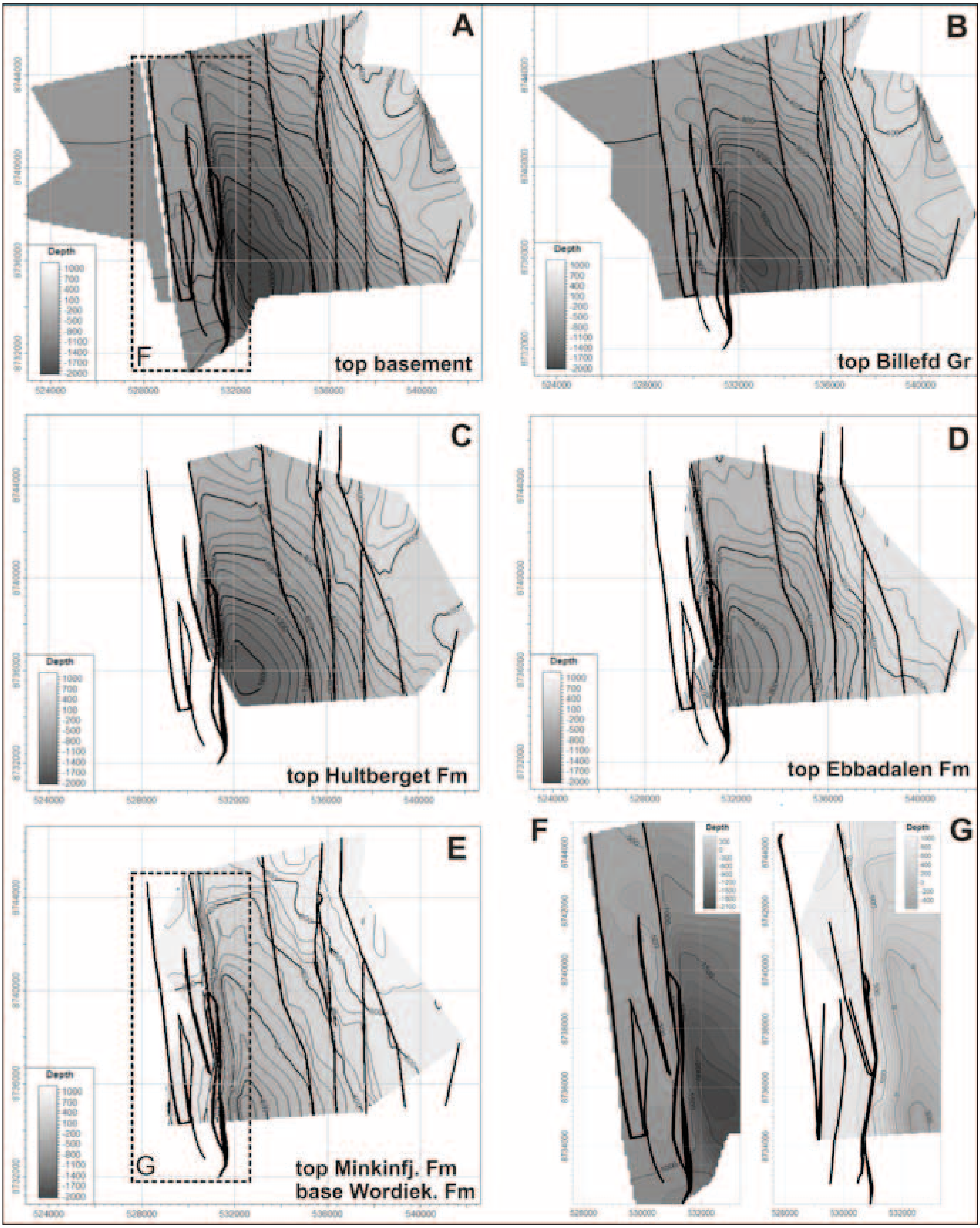

Figure 10. Isochore maps of marker surfaces with outline of faults. The underlying model is based on lidar scan interpretation of marker horizons, stratigraphic logs, cross sections, and some drill hole data. See Fig. 14 for details about the Lidar data. A) Top of metamorphic and Devonian basement, B) top of the Billefjorden Group pre-rift sandstone, shale and coal succession, C) Top of the early syn-rift Hultberget Formation, D) Top of the Ebbadalen Formation, E) Top of the Minkinfjellet Formation, equal to the base of the late-rift Wordiekammen Formation. F) Top-basement surface of the Billefjorden Fault Zone, showing the geometry of the Pyramiden relay zone. See map 'A' for location. G) Base-Wordiekammen Formation surface between the Billefjorden Fault Zone and the Petuniabukta syncline, showing the significant structural relief of this unit. See map 'E' for location.

Lithofacies associations and depositional systems

The syn-rift deposits of the Billefjorden Trough can generally be divided into four characteristic successions, or facies associations (FA1 to FA4, Figs. 11, 12 and 13). These are, in turn, interpreted to represent the main depositional systems that interacted during basin sedimentation. As the rift basin fill offers major and rapid lateral facies changes, there is a recurring difficulty of correlating units from the two sides of the basin. This is further expressed by transitional boundaries, which are common for the successions, with a few exceptions (further addressed below) that mark important basin-wide events. Below, we describe these facies associations in some detail. For further details on individual sedimentary facies, see Johannessen and Steel (1992), Dallmann (1999) and Eliassen and Talbot (2003a, b; 2005).

Facies association FA1: Arid alluvial fans

Towards the basin margins, thick sections of poorly sorted, immature, mostly very fine- to coarse-grained sandstone and conglomerate deposits dominate the basin fill. Typically, these sections consist of red-coloured, hematite-stained sandstone and conglomerate with subordinate, intercalated breccias and some mudstones. Individual bed thicknesses range from less than half a meter to several meters. The grains of the sandstones are angular to subangular while the texture varies from poorly to moderately sorted, occasionally very well sorted. Quartz, feldspar and mica are the major constituents. Meter-thick, massive layers of matrix-supported breccias with pebble- to cobble-sized fragments of basement and Devonian sedimentary rocks are locally observed near the marginal faults (Fig. 10A). They are typically found between lenticular-shaped sandstone beds (or layers) that often show basal scour, some with channel lags of poorly sorted gravel with up to cobble-sized clasts (Fig. 11). Other sandstone layers form sheets of better sorted sandstone, which are either massive or show signs of normal grading in combination with cross and parallel-bedding.

Johannessen and Steel (1992) describe some meters of thick, well sorted, fine-medium-grained sandstone layers with distinct cross-stratification. In places they are strikingly white, or whitish pink, as seen within the above-described fan successions. They have been interpreted as eolian dunes, which can be common features of coastal plain or playa settings (e.g., Magee et al. 1995). Some thin fine grained sandstones and mudstones contain calcite patches and nodules, indicating paleosol development (e.g., Kraus and Aslan 1993). Locally, coal fragments can be found and there are also layers with rootlets.

The red, immature sandstones reflect the proximal nature of these units, e.g. sediments derived from the nearby exposed bedrock. The intercalation of conglomeratic debris-flow deposits with poor to moderately sorted sandstones of fluvial origin indicates deposition on (semi-) arid alluvial fans with fluvial channels and associated overbank deposits, in accordance with previous studies (e.g. Johannessen and Steel 1992). In this scenario, the matrix-supported sedimentary breccias and poorly sorted sandstones point to a position near the apex of fans, whereas the relatively well-sorted pebbly and conglomeratic units represent adjacent, down-slope proximal fan deposits (Hooke 1967; Harvey 1987; Nemec and Steel 1984). Finer grained sediments such as lenticular sandstone layers represent stream channels on the middle fan. Similarly, the massive sandstone sheets are interpreted as sheet flood deposits, deposited during heavily sediment-loaded flash floods below the channel termination(s) on the fan or as crevasse splay deposits. Isolated conglomerates encased in finer clastic successions probably have a similar sheet flood or crevasse splay origin. Finer grained sandstone and mudstone are either deposited in the distal parts of the fan, towards the flood/coastal plain, or as overbank deposits on the medial or distal fan. In summary, the FA1 successions can be ascribed to an arid alluvial fan setting, with fans building in from the uncovered basin margins into the realm of a playa, or coastal plain (e.g., Magee et al. 1995).

Facies association FA2: Restricted marine basin/Playa lake

Locally, the basin offers exceptionally heterolithic sections (Fig. 7C and D, and Fig. 11C). These make up large parts of the lower Ebbadalen and upper Minkinfjellet formations and sections are characterized by interfingering of dm to m thick beds of variable red conglomerate and sandstone, green-gray sandstones, mudstone, micritic carbonate and gypsum. The red conglomerates and sandstones are similar to the ones described above (FA1 alluvial fan deposits). The yellow-green to grey sandstones are different. They are commonly massive and contain glauconite (Eliassen and Talbot 2003a). Characteristically, they occur in 1-2 meters thick beds (Fig. 7A) that have a fine to coarse grain size, with subangular to subrounded grains. Some pebbles and small clasts are locally found. Some sandstone beds show bioturbation, and locally host shell fragments. The sandstones are often associated with laminated claystone and mudstone, which occur mainly as thin, 10-30 cm beds, but can exceed one meter in thickness. Locally, these beds interfinger with evaporites. The claystones are black and organically rich, whereas the mudstones are commonly grey with plane-parallel lamination. The thicker, cleaner green sandstones have been ascribed to a shallow marine or shoreline setting (Johannessen and Steel, 1992), whereas the green-gray sandstones and mudstones are interpreted as low-energy tidal flat or marginal lake/playa deposits.

This section also offers some m-thick layers of yellow-gray grainstones and wackestones, dominated by plane-parallel lamination/bedding and a muddy matrix. They are often found interbedded with gypsum, anhydrite and dark micritic carbonate deposits (see description in FA4:

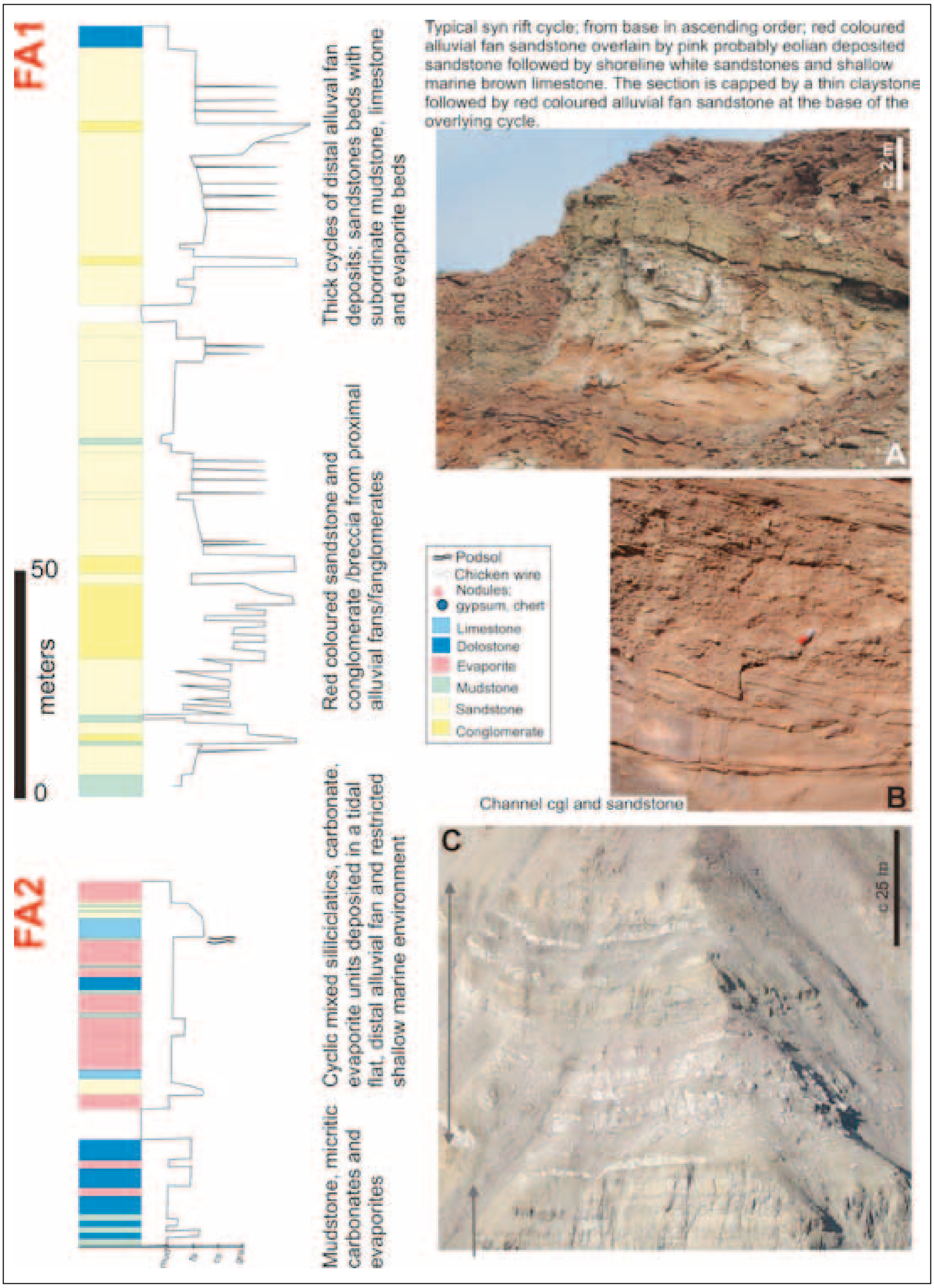

Figure 11. Examples FA1 and FA2; The log of FA1 is from the Pyramiden slope, with relevant photographs: Photograph A) shows a succession of red alluvial/fluvial coarse grained sandstones and pebbly sandstones followed by light red medium-grained eolian and shoreface (?) deposits, topped by dark grey marine limestone, then a thin claystone, before returning to the red alluvial deposits. The limestone contains brachiopod shell lags and bryozoa in a carbonate mud, with disarticulated and convex up shells, indicative of a high-energy, shallow marine setting (Sharp, pers. comm. 2011). B) Lenticular sandstone bodies, some with erosional bases and channel lag pebbles, interpreted as proximal to medial fan channel facies. Log of the highly heterolithic FA2 succession, as mapped in the Svenbreehøgda (located in Fig. 8). Photograph C) showing a lower section of meter thick layers of evaporite, carbonate and mudstone, and an upper more variable section dominated by evaporite, with some carbonate, mudstone and sandstone layers (parts of logged section).

sabhka), which further attest to a tidal flat or protected lagoon/lake setting.

Our interpretation of depositional environments for the individual facies suggests that FA2 represents interaction of the distal parts of alluvial fans with a restricted marine basin or playa lake. The latter offered coastal environments involving sabhka and lagoons as well as playa/ coastal plain.

Facies association FA3: Subtidal carbonate platform

There is a distinct micritic carbonate sequence in the lower Minkinfjellet Formation, which appears throughout the central realm of the basin. This unit varies in thickness from around 70 m in the west near Pyramiden to less than 12 m in the east, in Ebbadalen. Near Pyramiden, typical deposits are 70 cm to dm thick micrite carbonate layers separated by thin shale interlayers (Fig. 12A), whereas the eastern basin margin offers more siliciclastic units interfingering with the carbonates. There, the micritic carbonates are in places interlayered with meter-thick grainstones and

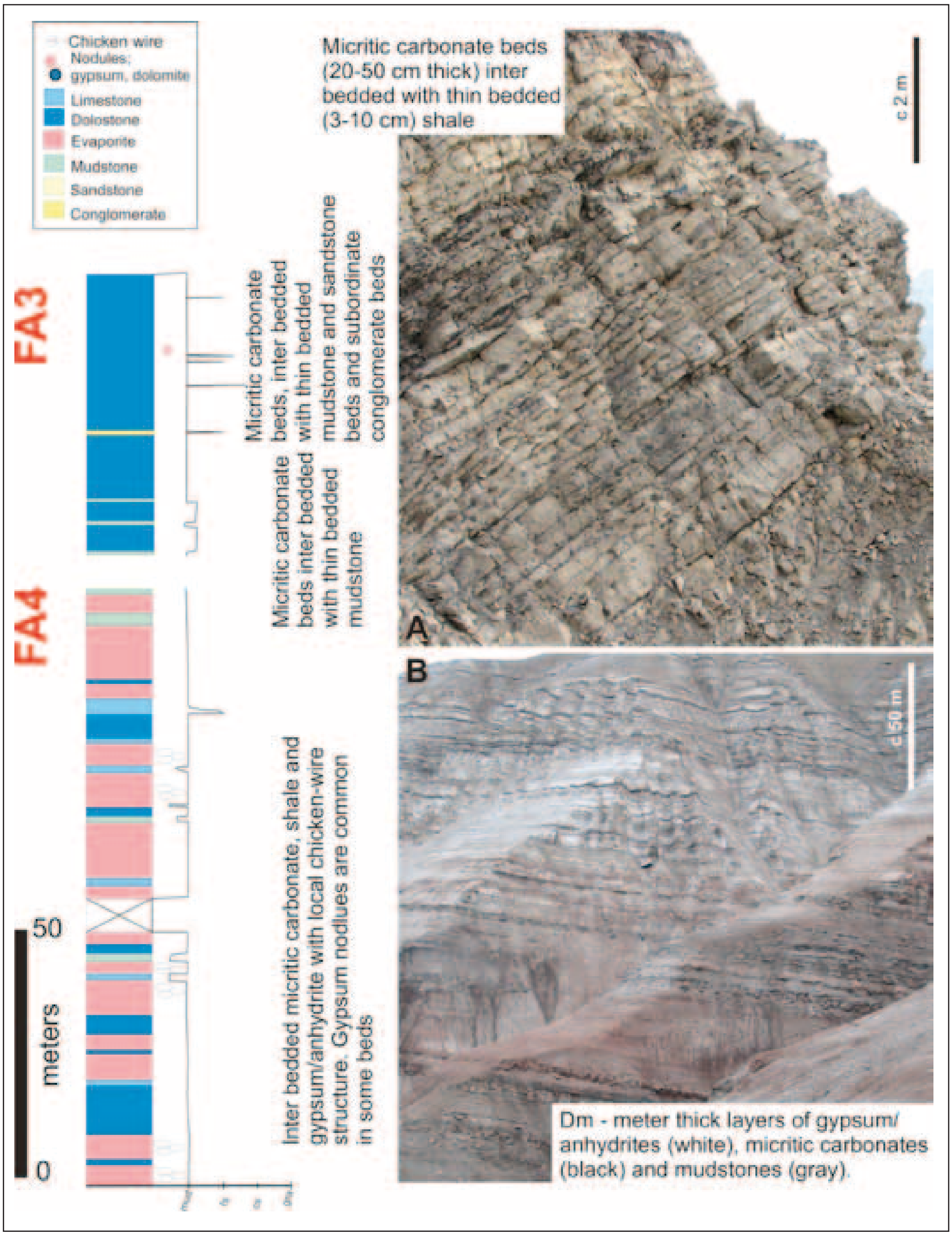

Figure 12. Examples of successions represented by FA3 and FA4; The FA3 log from Pyramiden shows mainly thin micritic carbonate with thin, dark shale interlayers, as seen on the photograph (A). The FA4 log from Ragnardalen sub-basin is distinctly made up of fine grained lithologies, with a dominance of evaporite, and with carbonate, shale and some mudstone layers. The photograph (B) shows this succession in the upper Ebbadalen Formation of Ragnardalen (footwall of Løvehovden fault), with white and pink evaporite, pink and dark grey shale (partly pink paleosol layers), and black carbonate layers.

wackestones. This FA3 carbonate section is interpreted as a subtidal carbonate platform in the west (Eliassen and Talbot 2003a), but is transitional into shallower marine and coastal settings eastwards. Here, it is similar to the FA2 restricted marine basin towards the eastern basinal margin.

Facies association FA4: Sabhka

This succession has some similarities to the heterolithic FA2; however, the succession is fully made up of mud and clay fraction lithologies that occur as laminae to beds up to 10- 40 cm thick (Fig. 12B). Minimal siliciclastic input hints at a position away from major alluvial fans or deltas, or a basin setting with minimal relief. Gypsum and anhydrite (evaporite) deposits make up the major constituents of the basin, especially in the central realm. Gypsum beds are either structureless with a crystalline appearance with few or no primary features, or nodular, with a characteristic "chickenwire" structure (Eliassen and Talbot, 2003a, their Fig. 11B). Some observed beds of gypsum show plane-parallel or wavy lamination interbedded with nodular or crystalline gypsum. Nodular chickenwire gypsum is generally thought to be the result of displacive growth of gypsum in muddy sediments on a supratidal mudflat (Kendall & Warren 1988), or formed in subaqueous environments such as saline ponds and lagoons. Thicker gypsum beds are thought to have been deposited in a subaqueous environment, whereas plane-parallel laminated gypsum indicates a subaquatic depositional setting. Here gypsum precipitates in a hypersaline water column and settles to the bottom (Dean & Anderson 1982). Overall, tidal flats associated with a restricted hypersaline bay or lagoon is the supposed environment for the evaporite deposits, with the mentioned interbedding with mud reflecting climatic or seasonal variations. A playa setting is also conceivable.

Pure carbonate mudstones occur as isolated massive beds in gypsum or subordinate sandstone-dominated successions, but can also be found as a distinct succession in the lower Minkinfjellet Formation (see FA3 above). The micrite beds are commonly dm-thick, with a dark grey or black color. Locally, they host gypsum or chert nodules giving them a mottled appearance. The beds are made up of calcite, more or less replaced by dolomite, and are in general free of fossils. Deposition of calcareous muds is normally restricted to low energy protected environments, such as lagoons, or in offshore subtidal environments. According to Eliassen and Talbot (2003a), the association with mudstone and gypsum beds of sabhka origin supports the interpretation of lagoonal deposits, which would also provide restricted conditions favoring accumulation and preservation of organic material.

Interplay of rift successions

The spatial/temporal distribution and interaction of depositional environments and resulting stratigraphic architecture are largely controlled by the balance between accommodation space creation and sedimentation rate; which in turn are predominantly governed by the interplay between eustatic sea-level changes, climate and tectonic controls (e.g., Gawthorpe and Leeder 2000; Densmore et al. 2007). In the Billefjorden Basin, unique exposures along and adjacent to the major, basin-margin fault-tip fold system allow a comparison/correlation between observed fault-fold patterns and depositional parameters such as facies thickness variations and stacking patterns (Figs. 13, 14 and 15).

The syn-rift succession (Hultberget, Ebbadalen and Minkinfjellet formations) is less than 700 m thick in the east, and clearly thickens towards the BFZ in the west. Subsidence along the BFZ was asymmetric and larger in the south (Fig. 10), evidenced by thickening of the entire syn-rift succession from 1000 m in the north to a tentative maximum thickness of more than 2000 m in the south (Fig. 16). Within this succession, the Ebbadalen Formation thickens from less than 200 m in the east and north to nearly 700 m in the SW. However, the Minkinfjellet Formation exhibits a different pattern, thickening from 200-300 m in the east to around 700-800 m nearer the BFZ. When comparing the thickness variations, the patterns suggest that much of the observed asymmetry of the Billefjorden Trough, as reflected in its overall half-graben geometry, developed during deposition of the Ebbadalen Formation, and was further enhanced during formation of the Petuniabukta syncline, that developed until Wordiekammen Formation age. Depositional architecture of the Minkinfjellet Formation suggests a mild asymmetrical subsidence, with most subsidence along the BFZ in the NW of the study area, which is likely to have been caused by movements on both the BFZ and the Løvehovden fault (see below).

In the Pyramiden mountainside, proximal to the basin-controlling fault system, the structurally identified relay zone exhibits a succession of stacked alluvial fan deposits dominated by FA1 (Figs. 11 and 14). In general, these fans thin towards what would be their apexes to the NW. The lower fan successions distinctly wedge out towards a fault in the west, with sections warped up along the fault and considerably condensed. Some of the upper fans overstep this fault (fault A, Fig. 14).

Our strip logs in Fig. 14 reveal a lower fan section characterized by heterolithic FA2 type deposits overlain by stacked alluvial fan facies (FA1) which thicken up-section. These are separated by coastal-marine units (FA2) consisting of 2-5 m thick sections of white-green sandstone (foreshore-upper shore face, or partly eolian) (Johannessen and Steel, 1992) overlain by marine wacke-/grainstone, where fully developed, or preserved.

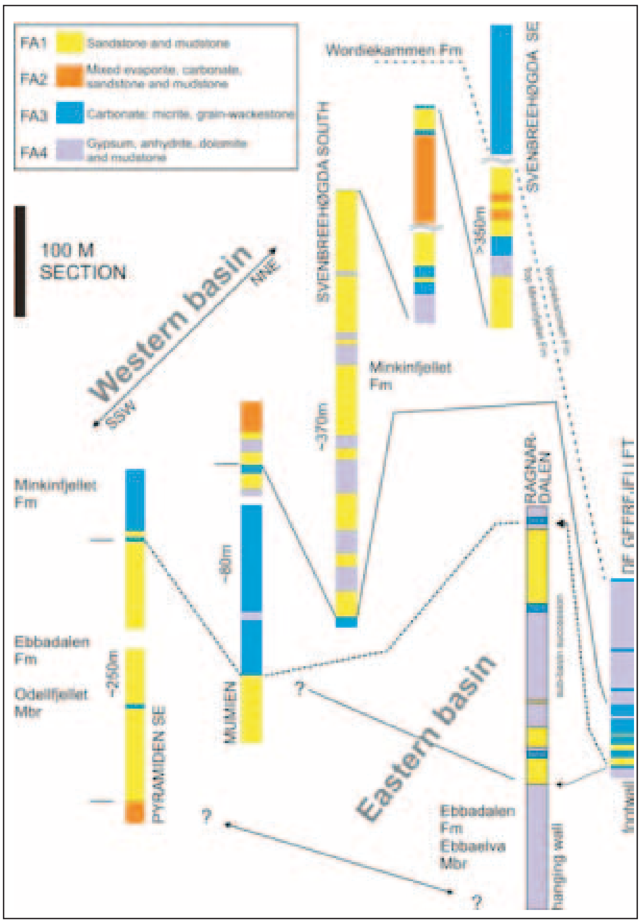

Figure 13. Schematic compilation of stratigraphic logs and W to E description of lithostratigraphic facies associations FA1 to FA4 of the Billefjorden Trough. The logs are located in Fig. 8 as white lines.

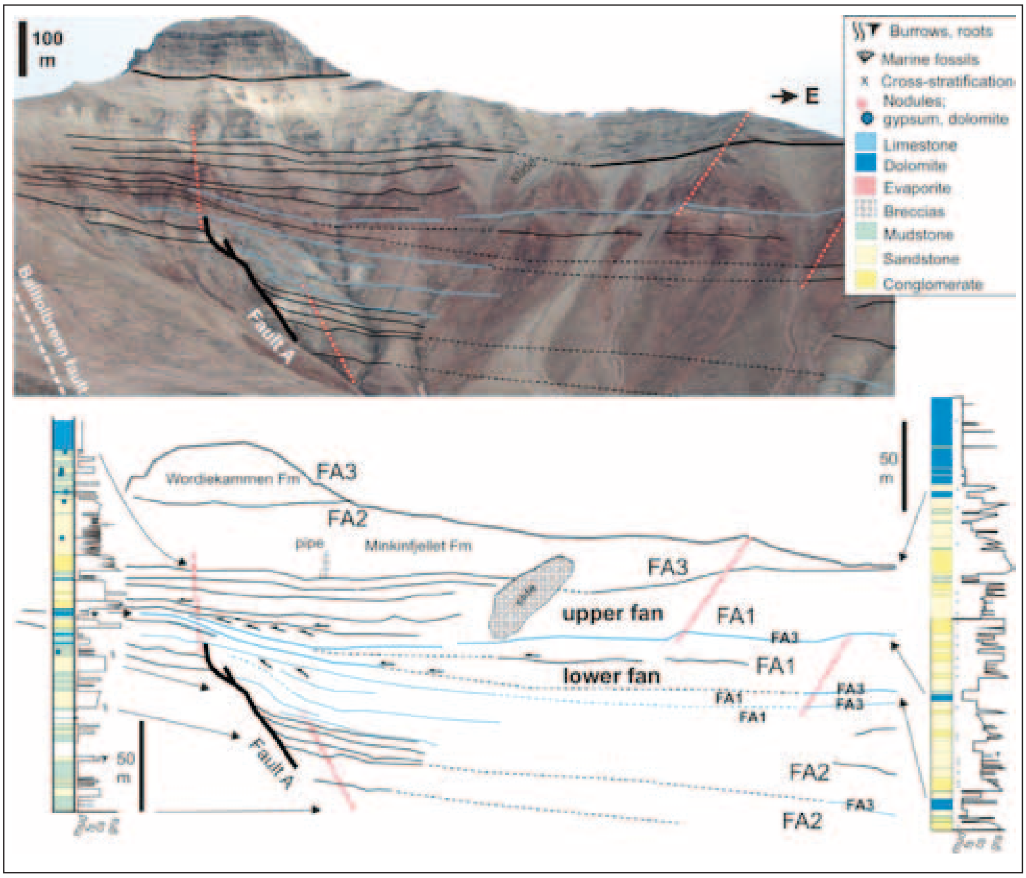

Figure 14. Photograph of the Pyramiden mountain side, and line drawing based on the photograph showing main depositional units. The view is from the south, which gives an oblique angle to the dip of bedding. The logged sections are located as red, dashed lines on the photograph. Note the upward thickening red sandstone successions of the Ebbadalen Formation, separated by marine carbonates (blue lines), of which the lower units are dragged up along and thinning towards the fault (Fault A). The red sandstones are interpreted as alluvial fan deposits building out from an apex in the upper left, down towards the lower right. The fans build out from, and down a relay ramp situated between the two major fault segments of the BFZ, the Balliolbreen and Odellfjellet faults (not on photograph).

Two of the fan sequences are very well exposed, showing thicknesses of 50-100 m (lower and upper fan of Fig. 14). The lower fan thins towards - but oversteps - the local fault (fault A, Fig. 14) in the west and expands towards the east. The eastern logs display a basal coarsening upwards in section followed by two overall fining-up successions separated by thin conglomerate beds. The second fining-up succession is topped by marine deposits. The upper fan is more complex, starting with a coarsening upwards succession above a sharp base, and followed by a series of thick, interfingering, sandstone, pebbly sandstone and conglomeratic beds. The upper half of the upper fan shows two fining-up successions above sharp contacts; both successions are divided by conglomeratic beds. At the top, the fan sharply transgresses into carbonates of the Minkinfjellet Formation.

In contrast to observations made further east and lower on the fans, deposits in the western part are characterized by sharp and erosively based immature sedimentary breccias and conglomeratic units exhibiting no evident grain-size trends. Coarse clastic beds generally display normal grading towards their tops. Interbedded fine-grained sandstone and rare mudstone units are commonly massive or finely laminated. The upper fan building across the smaller fault A (Fig. 14) illustrates these depositional characteristics particularly well. The overall pattern of the red succession dominated by FA1 in the Pyramiden mountain side, shows that breccia and conglomerate are encountered close to the apex of the alluvial fan, where the gradient is at its highest (5-10° expected for arid fans; Hooke 1967).

In places the red FA1 sandstones show a sharp interfingering with carbonates, consistent with repeated flooding of fan surfaces during interaction with marine conditions. Characteristically, this section starts with the FA1 succession, overlain by local eolian sandstones, then a foreshore or shore face sandstone deposit, a thin shale, and finally grey shallow marine limestone. This succession is topped by a thin claystone before returning to the FA1 sandstones, as shown in Fig. 11A. This suggests that outwash events with related sediment lobes on the fan at times interacted with both the tidal flat and marine realms.

The stratigraphic successions observed along the BFZ show a distinct down-stepping of marker beds from the basin margin towards the centre (Fig. 13). For example, when tracing the basal micritic carbonate section (FA3) of the lower Minkinfjellet Formation from the Pyramiden area towards the NNE, this section occurs at successively lower levels before disappearing in the subsurface. In parallel, a significant thickening of the heterolithic succession above the FA3 micrite section from around 100 m in the Pyramiden slope (Eliassen and Talbot, 2003a) to more than 400-600 m in the NNE, at Svenbreehøgda, is evident. This stratigraphic interval also shows a change from heterolithic fan – tidal flat deposits (FA2) and the sabhka type (FA4) successions encountered near Pyramiden to mainly FA1 alluvial fan deposits divided by thinner FA4 sabhka deposits in the

NNE direction. This overall thickening and related change in facies associations suggest contemporary movements of fault segments within the relay zone between the Balliolbreen (in the SSW) and Odellfjellet faults (in the NNW). Thicker successions are deposited in the synclinal hinge of monoclines rather than next to faults. Noticeably, the thick FA1 alluvial fan deposits correlate temporally with the upper Minkinfjellet Formation. This suggests that the NNE part of the relay zone acted as an oblique sediment feeding point for the Billefjorden Trough at this time, as addressed in the Discussion.

Further east, in the central area of the Billefjorden basin, lithofacies associations suggest an overall low-energy coastal environment (Fig. 13). Sabhka-fan facies FA2 is found in the lower Ebbadalen Formation and in parts of the Minkinfjellet Formation, and sabhka facies FA4 is encountered in the upper half of the Ebbadalen Formation and parts of the Minkinfjellet Formation (Johannessen and Steel, 1992). Shifts in the depositional environments are best illustrated near faults, such as along the Løvehovden fault, exhibiting the Ragnardalen sub-basin in its hanging wall. As described by Maher and Braathen (2011), the footwall (eastern) shoulder displays a 5-20 m thick section of strataform breccias and an associated 20-30 m deep incised valley, consistent with periods of emergence of the footwall block. The fill of the hanging wall sub-basin is around 200 m thick and increases to the south.

The basal section under the sub-basin is characterized by FA4 sabhka deposits. In the strip log (Fig. 15), this unit is interpreted as part of the upper Ebbadalen Formation as it seems to predate movements along the Løvehovden fault. This is corroborated by the fact that this sabhka lithofacies can be found in the footwall below the breccias, although the base of the breccias truncates this succession at a very low angle towards the Løvehovden fault, attesting to footwall rebound-related uplift. The onset of subsidence of the sub-basin is probably marked by the introduction of thicker mudstones within the evaporites (above 100 m in the log of Fig. 15). This is succeeded by green, marine sandstones which mark the beginning of a 10 m thick, heterolithic, fining upwards section topped by micritic carbonate and evaporite. Overlying this is an FA1 type alluvial/fluvial, red sandy facies in a thin coarsening upwards unit, followed by another fining upwards section containing conglomerates and pebbly sandstone in its lower part. Above this, the sub-basin fill consists of FA4 evaporites, micrite and grainstone (wackestone) with some thin mudstone interlayers, especially in the lower part. Near the top, the FA1 red sandstone with fining-upwards sections reappears, as well as three alluvial fan cyclic units ending in marine micrite. The sub-basin succession is terminated by the FA3 i.e. regional micritic carbonates of the lower Minkinfjellet Formation. This unit is thinner and more heterolithic on the footwall block.
The overall FA1 red sandstone fining up successions of the Ragnardalen sub-basin likely reflect progradation of alluvial

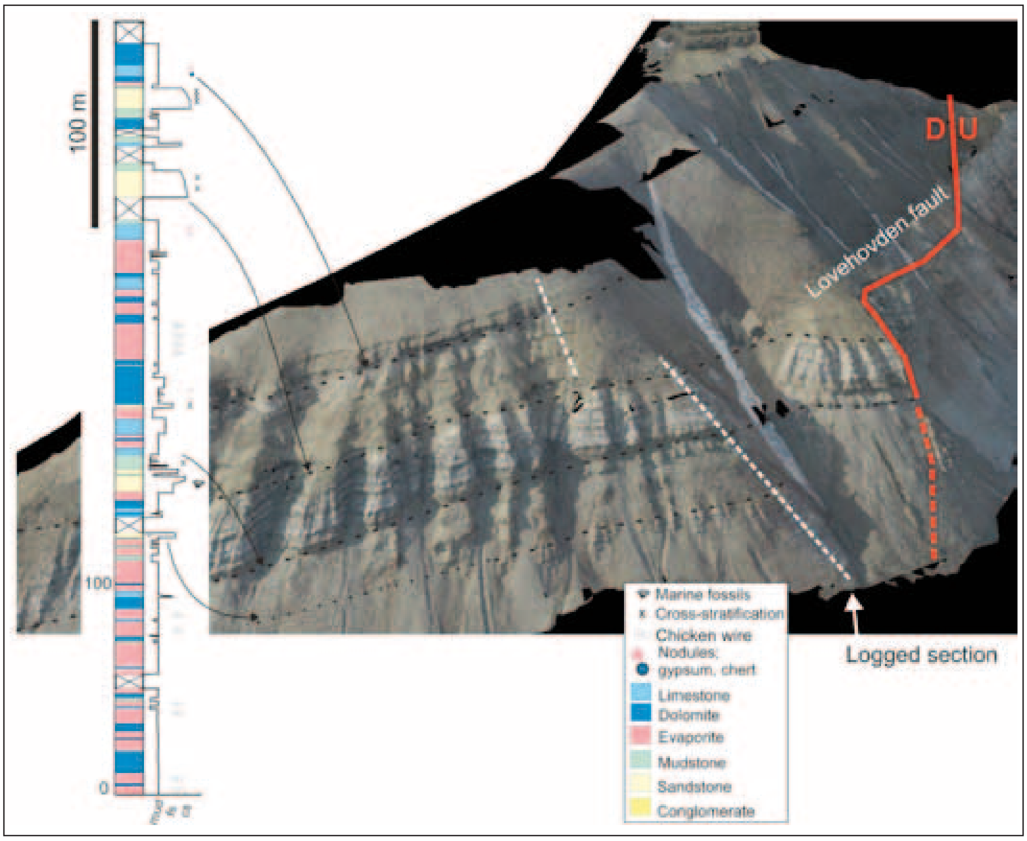

Figure 15. Image of Lidar-based photorealistic model of the Ragnardalen sub-basin in the hanging wall of the Løvehovden fault, as seen from the south. The logged section is located on the photograph (white dashed lines). Note gentle thickening of sandstone dominated successions towards the fault. The Lidar data were collected from an oblique helicopter-mounted platform (Buckley et al., 2008b), and were later processed into 4D models using the methods described in Buckley et al. (2008a, b).

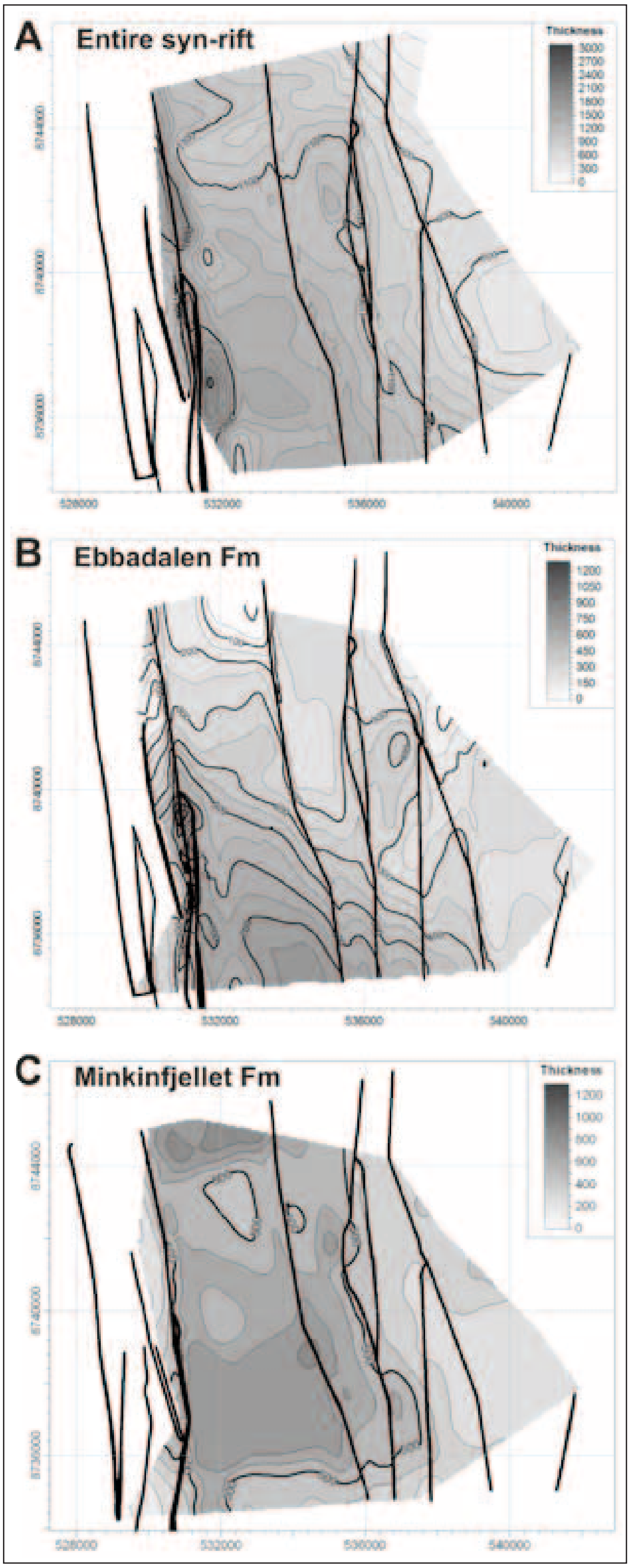

Figure 16. Isopach maps from the basin model; (A) the entire syn-rift succession of the Hultberget, Ebbadalen and Minkinfjellet formations, (B) the Ebbadalen Formation, and (C) the Minkinfjellet Formation. The isopach maps are derived from the surface maps of Fig. 10.

fans along the hanging wall basin of the Løvehovden fault. As opposed to the large Pyramiden fans, there are no coarse clastic spikes in the fining up successions, and the fan cycles are generally thinner, which suggests a distal position relative to the sediment entry point, or, alternatively, limited relief. This is also mirrored by the middle, FA4-type evaporite-carbonate section of the sub-basin, which represents alternating sabhka flats and shallow marine incursions. In summary, there is a clear difference between the characteristics of the Pyramiden and the Ragnardalen sub-basin sections (Fig. 14 vs. Fig. 15). This reveals the difference between a setting proximal to the basin-bounding fault system, characterized by steeper gradients, and settings distal with respect to the continental source area, signifying low angle hanging wall dipslope depositional systems.

Discussion

In the following, we discuss the relationships between extensional fault growth and fault-tip fold development. Contrary to the commonly observed fairly gentle, concentric geometry of extensional monoclines seen in many basins world wide (Withjack et al. 1990; Sharp et al. 2000; Gawthorpe and Hardy 2002; Khalil and McClay 2002), the Billefjorden Trough offers intense folding with narrow hinges and steep forelimbs paralleling the controlling fault. The growth and interaction of faults and associated extensional fault-propagation folds is attested by alluvial fans along the basin margin; these alluvial fans are basically relay ramp facies associations, which can be used to unravel temporal sediment fairways and subsidence rates.

Patterns of fault growth versus basin fill

The Pyramiden section and its relationships to the mapped strands of the basin-bounding fault complex exemplify the interaction between fault growth, monocline development both along fault segments and in relay zones, and the effects on deposition. Growth of monoclines is typically characterized by deposits that "wedge" (onlap) towards the fold, as shown for example for syn-rift units of the Suez rift by Sharp et al. (2000). In the Pyramiden slope, this is well expressed for the lower alluvial fans, which all thin towards the fault in the west (Fault A, Fig. 14). Basin models (Gawthorpe and Leeder 2000; Sharp et al. 2000) predict that in the subsequent stages of fault growth, strain localization and linkage during additional slip occur until a through-going fault zone is developed (Watterson 1986; Walsh and Watterson 1988; Walsh et al. 2003; Nichol et al. 2005). When such master faults are in place, isolated smaller segments tend to be abandoned, and continued displacement becomes localized along the through-going master fault(s), thereby initiating a phase of focused deformation signaled by considerable vertical movements. In the case of Pyramiden, the upper alluvial fan complex covers the smaller fault (fault A) without signs of subsequent fault activity, suggesting that this structure was abandoned. Instead, the fan has its apex near the Balliolbreen master fault farther west; hence this fault was

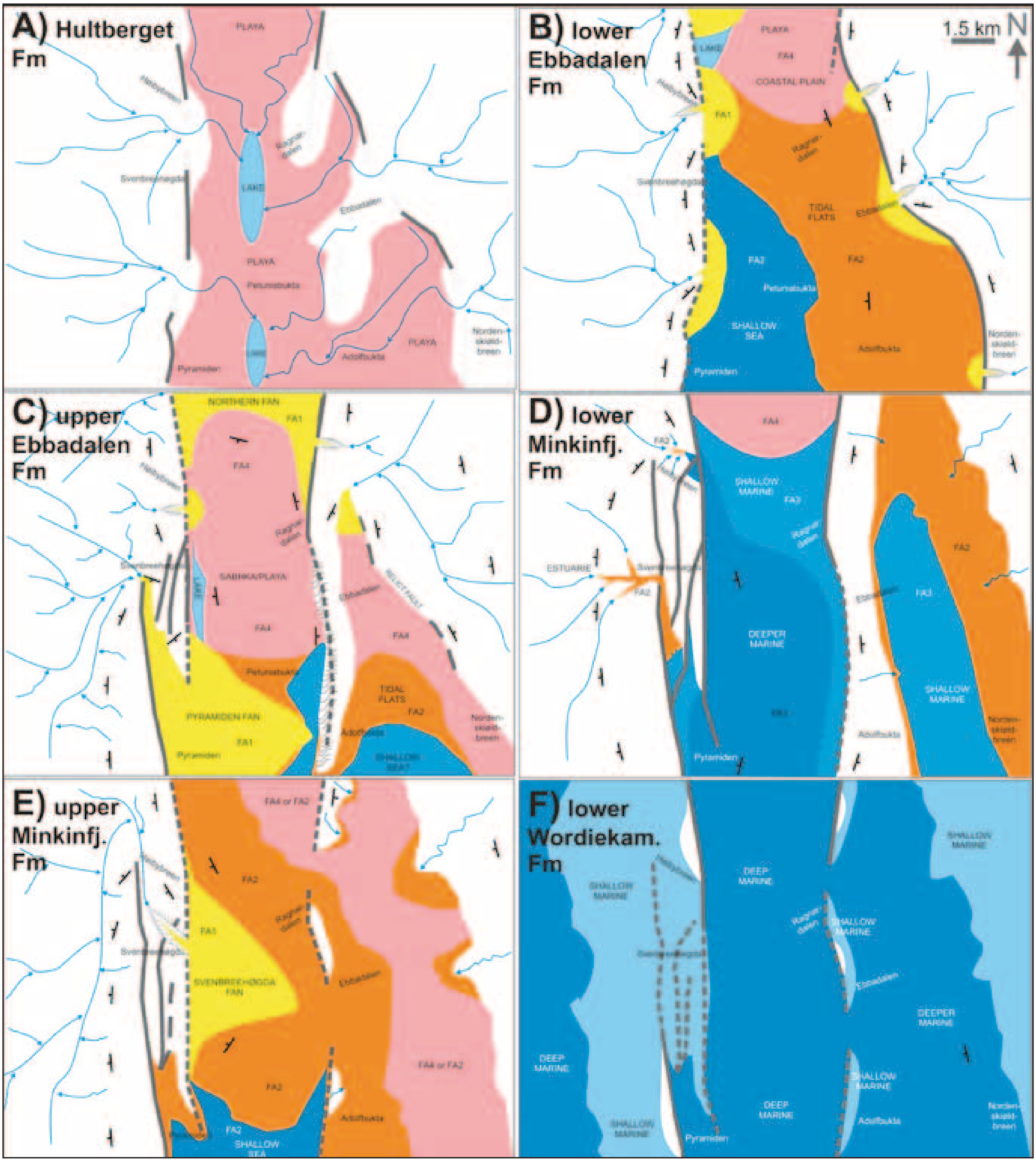

Figure 17. Palaeo-geographic basin reconstructions, highlighting active faults (gray solid lines), growth of fault-tip monoclines (gray, dashed lines) and the distribution of the characteristic depositional systems, including FA1 to FA4. The events covered are; A) Hultberget Formation, B) Ebbaelva member, lower Ebbadalen Formation, C) Odelfjellet/Tricolorfjellet Member, upper Ebbadalen Formation, D) Corronelva member, lower Minkinfjellet Formation, E) Terrierfjellet Member, upper Minkinfjellet Formation, and F) lower Wordiekammen Formation. Light blue – lake, pink – playa, yellow – alluvial fan complex, orange - tidal flats, blue – shallow marine, dark blue – deeper marine, white – terrestrial.

accumulating displacement at this stage. This development is interpreted to indicate that the Balliolbreen and Odellfjellet faults had started to link up to form a through-going fault. Fault linkage accelerated offset by focused fault movement and thereby enhanced the basin subsidence, which is likely reflected by the substantial marine flooding associated with deposition of the regional FA3 marine carbonates of the lower Minkinfjellet Formation. These are thickest towards the master BFZ in the west, attesting to asymmetric subsidence with the fill wedging away from the fault.

Of special interest is the fact that this is the first basin-wide event in which marine conditions are juxtaposed with the faults, which denote a marked change in the character of the basin. Both before and after this event, the depocenter seems to have a lenticular shape, with accommodation space offset from the faults by the fault-tip folds (see below). This event also caused a termination of the FA1 fan complex and related marine sandstone deposition, suggesting redirected footwall drainage away from the area. This again could relate to footwall flexural rebound caused by focused faulting on the breached relay zone.
In the same time period as a trough-going BFZ developed, the Løvehovden fault was activated, thereby narrowing and focusing the area of basin subsidence. This caused a shift from asymmetric subsidence with most accommodation space developed next to the faults in the west (Fig. 16B) to more symmetric subsidence of the central realm (Fig. 16C). As a consequence, the east-central basin margin became exposed, probably re-directing the drainage in this area from overall westerly flow down towards the half-graben centre to an easterly and more complex pattern away from the footwall rebound-related uplift. Dissolution surfaces (strataform breccias) and the paleo-valley of the footwall domain to the Løvehovden fault lend support to such a change (Maher and Braathen, 2011). This is likely to have caused a reduced clastic input to the eastern side of the depocenter, which appears to be corroborated by the thick FA4 sabhka facies succession encountered in the Ragnardalen sub-basin.

Temporal fault movement played a key role for the development of clastic fairways into the basin. For example, the abovementioned fault-breaching of the Pyramiden relay zone seems to have modified the footwall drainage. On a broader scale, there is a notable change in the degree of the BFZ footwall uplift along strike from the north to the south. In areas of major footwall rebound, setting up fault-perpendicular anticlines (Gawthorpe and Leeder 2000), such as in the south around Pyramiden, the Billefjorden Group is missing in the footwall and the Wordiekammen Formation rests directly on the basement (Figs. 4 and 8). Northwards, there is an E-W trending footwall syncline in which Billefjorden Group rocks are preserved, attesting to less fault movement. This speaks both for the development of source areas and sedimentary catchment dynamics of the Nordfjorden block.

In tectonically driven basins the importance of global sea-level variations may be difficult to predict (e.g., Gawthorpe et al., 1994). The above relationships do, however show that in the Billefjorden Trough, faulting and folding, and variable sediment flux into the basin, were important controls on the subsidence and developing accommodation space. Another important parameter may be lithology-dependent, variable subsurface compaction. For example, gypsum muds could compact as much as 80% during the transition to anhydrite (e.g., Murray 1966), whereas sandstone would compact to around 30% (Ramm and Bjørlykke 1994; Chuhan et al. 2002; Sougue et al. 2010). In addition, stratiform breccias attest to significant removal of material, which could have further contributed to subsidence, especially later in the basin evolution.

Eustacy and climate versus fault-controlled basin development

The above discussion highlights fault growth as the main mechanism behind flooding of the alluvial fan system. However, eustatic sea-level rise could be of significance, for instance, for the basal marine carbonate section of the Minkinfjellet Formation as well as for the thinner marine carbonate layers of the alluvial fan system of Pyramiden. Noticeably, the Early Carboniferous experienced a gradual lowering in first order eustatic sea-level (e.g., Haq and Schutter, 2008), with a low-stand in the Serpukhovian-Bashkirian, as shown in Fig. 5. A subsequent mild increase in sea-level coinciding with enhanced cyclical changes developed towards the Permian, with a high-stand in the Gzhelian-Asselian. In light of the eustatic low-stand, combined with a basin fill signal consistent with topographic relief especially along the western basin margin, we suggest that the syn-rift succession was overall fault-controlled, as also advocated by Johannessen and Steel (1992). However, individual flooding events may have been enhanced by short-term sea-level high stands. Eustatic impact is more likely for the thick carbonates in the lower Minkinfjellet, which have a basin-wide occurrence, although a thickening of this unit towards the BFZ suggests asymmetric basin floor subsidence, as would be expected by faulting. On the contrary, the thinner shallow-marine carbonate layers that punctuate the alluvial fan system of Pyramiden cannot with certainty be correlated across the basin to the eastern dipslope, which could be seen as a sign of localized subsidence and flooding along the BFZ. However, the lower relief hanging wall dipslope to the east presents many thin, marine carbonate layers interfingering with evaporites (Johannessen and Steel, 1992), in sum indicating a series of flooding events. The controlling factor for this cyclic pattern remains open; however, fault-driven subsidence in periods of high seismic activity could out-signal eustatic changes.

In addition to fault-driven subsidence and eustacy, climatically induced change could have a profound effect on the magnitude and/or time distribution of sediment and water discharge, as well as catchment development (e.g., Crossley 1984; Mack et al. 1994; Densmore et al. 2007; Armitage et al. 2011). The described syn-rift succession of the Billefjorden Trough shows few if any signs of major changes in climate, such as high lake-level deposits (prograding lake shore lines and deltas) in the basin centre, temporal development of eolian dunes or marine reefs, or major incisions for instance in the basin margin fan complexes (e.g., Mach and Leeder, 1998). Possible climatic signals of proximal fans could include periodic denudation events in the form of debris flows, although these deposits could also be related to ground motions from earthquakes. Similarly, the increased thickness of the upper two fans in the Pyramiden slope could reflect increased sediment discharge from tributaries that experienced increased precipitation. On the contrary, significant incisions could have signaled reduced sediment discharge and (or) higher water supply. Notably, major incisions have only been recorded in footwall uplift to the east. With a lack of obvious or strong signals of climate change, we conclude that the Billefjorden Trough experienced a fairly stable arid climate during its accumulation of sediments, although we acknowledge that our regional dataset limits resolution for detailed, short-term analysis.

Style of faulting and folding: control by basin fill

It is questionable if the BFZ ever significantly emerged as a fault scarp or whether the fault margin was expressed as a flexure through most of the basin evolution. The general anticlinal geometry of the basin fill around Pyramiden and the Petuniabukta syncline with its steeply east-dipping limb in the hanging wall of the Odellfjellet fault both attest to major monocline(s) developing along this side of the basin, especially in the central and northern realms (Figs. 6C and D, 7 and 8). However, the structural style of the Balliolbreen fault to the west is different, without signs of major fault-tip folding of units in the proximal hanging wall, although this may change along strike to the south, where this structure becomes the master fault (Bælum and Braathen, in press). North of Pyramiden, the syn-rift succession in the hanging wall to the Balliolbreen fault wedge out, likely reflecting overall footwall uplift of the basin margin with erosion and bypassing of sediments in a proximal position to the source area. The brittle style of the Balliolbreen fault suggests this fault developed a scarp, unless the small displacement towards the northern fault tip was overstepped by sediments.

The major fault-tip folding of the Odellfjellet fault contrasts with a simple fault scenario in which there is hanging wall rotation and strata dip towards the fault, and where maximum accommodation space is developed right next to the fault, such that the maximum thickness is along the fault, from which sedimentary unit thin away (e.g., Sharp et al. 2000). Instead, the western margin of the Billefjorden Trough shows that the entire stack of strata dip away from the faults, with alluvial fans and other successions that thicken away from the fault source (e.g., fans of Fig. 14). The overall pattern is that of maximum accommodation space displaced towards the hanging wall side, setting up an asymmetric, lens-shaped basin fill. Similar offset basin fills are described from the Suez Rift (Sharp et al. 2000; Jackson et al. 2006).

The major Petuniabukta syncline in the hanging wall of the Odellfjellet fault, which experienced more than 1000 m fault-driven subsidence, is likely associated with significant thicknesses of plastic lithologies. Both evaporites in the Minkinfjellet Formation and in the underlying Ebbadalen Formation (seen as mainly evaporite sections in drill core) could have influenced the structural style as this monocline gradually developed in Wordiekammen Formation times. A mechano-stratigraphic control on the style of faulting in the central basin realm can be exemplified by the Løvehovden fault, which presents a monocline that diminishes northwards and is replaced by a brittle fault in Ragnardalen. The common observations are that parts of basins with weak, plastic units such as evaporite and shale, where the fault has a low propagation to throw ratio, experience significant folding around fault tips before the fault breached the succession (e.g., Withjack et al. 1990; Sharp et al. 2000; Gawthorpe and Hardy 2002; Khalil and McClay 2002; Finch et al. 2004). On the contrary, where stiffer, more brittle units such as sandstones and massive carbonates are separated by thin plastic units, brittle faults develop without much folding. The along-strike shift in structural style for the Løvehovden fault suggests that evaporites dominated the hanging wall basin in the south, for example in Ebbadalen. There, the c. 250 m thick Ragnardalen sub-basin is made up mainly of stratiform breccias derived from evaporites and carbonates. In contrast, the around 200 m thick succession of the sub-basin in Ragnardalen farther north offers two siliciclastic successions (Fig. 15) that were probably significantly stiffer. A similar pattern is also suggested across the basin where there is a profound difference in fault style between the central realm, characterized by fault-tip folds and distinct shearing in evaporites, and the eastern basin margin showing mainly brittle faults. The latter area experienced significant clastic input down the basin's dipslope. Similar conclusions around changes in structural style, controlled by the effects of changing lithologies, are drawn by Jackson et al. (2006) from studies of comparable monoclines in the Suez rift area. Further, localized shear in weak lithologies probably caused vertical fault segmentation. For example, in the Løvehovden fault-tip fold (Fig. 2) there are faults terminating in the fold limb, including one fault that is rotated with bedding into a "reverse" fault orientation, consistent with vertical segmentation during fault and fold growth. For the major Odellfjellet fault-tip fold (Petuniabukta syncline), extensive layer-parallel normal shear in evaporites in the steep fold limb suggests that there is a layer-parallel detachment in this position (Fig. 7C and D). This shear zone likely triggered and rooted faulting in the proximal footwall region of the Odellfjellet fault, similar to the conceptual model for structural style advocated by Jackson et al. (2006).

Alluvial fans and accommodation space

Three major alluvial fan systems are proposed for the basin, all building out to the east and southeast: (i) the Pyramiden relay fan of the Ebbadalen Formation, (ii) the Svenbreehøgda relay fan of the upper Minkinfjellet Formation, and (iii) a northern fan complex documented by Johannessen and Steel (1992; their Fig. 8 Odellfjellet log). These fans attest to a large flux of sediments, suggesting that they may have been building out across the entire trough. As these arid fans probably attest to fairly episodic, rapid sediment supply to the basin, with stacked depositional cycles suggesting aggradation partly combined with progradation (Johannessen and Steel, 1992), they variably kept up with the developing accommodation space or prograded into the basin. These large alluvial fans were not only important fairways for siliciclastic sediments into the basin. As they were buried, their lower potential for compaction compared to neighboring evaporites would cause differential subsidence, with the sandstone-dominated relic fans potentially forming gentle ridges. These ridges, in turn, likely influenced the distribution of later sedimentary systems. This is depicted in the basin reconstruction of Figure 17.

The Pyramiden composite relay fan shows a pattern of stacked successions; each cycle topped with marine deposits, which is consistent with repeated transgressions with general retreat of the fan during relative sea level rise. This flooding would allow time for reworking of former fan deposits and maturation and redistribution of these sediments over larger parts of the basin. Sediment remobilization would also be expected from slumping of fan material, for example during seismic events; a common mechanism adjacent to fan deltas (e.g., Nemec and Steel 1988; Sharp et al. 2000). The flooding scenario would thus favor a basin with FA1 fan succession interfingering with the heterolithic FA2 successions, whereas the FA4 sabhka successions would be suppressed. The opposite signal in the sedimentary record could be expected if the subsidence and/or transgression was rapid, for example triggered by a brisk series of fault ruptures, as could be expected when faulting localizes on to a master fault (Gawthorpe and Leeder 2000). In this scenario, with arrest of clastic sediments to the basin margin, there would be less clastic material reaching the basin center, promoting deposition of FA4 sabhka facies in central, marginal marine parts of the basin.

Fault propagation, sediment supply and subsidence

Directly linking fault movement (rupture or flexure) with depositional response within a developing accommodation space is not trivial. This discussion can best be addressed through observations in the Pyramiden alluvial fan complex. These fans show thinning to the west to northwestward, and towards the basin bounding faults which provide a spatial and geometric link between faulting and deposition. Further, the overall 15-20º SE tilt of the basement surface and bedding in the pre-rift/early-rift sedimentary succession, oblique to the N-S striking faults, attest to a position in a relay ramp (Figs. 6B and 10). Since sediment supply to the axial system is common through relay zones (Gupta et al. 1999), such zones provide siliciclastic material that in many cases propagate further into the realm of the basin than into surrounding regions.

The topography of a relay ramp, which develops a syncline-anticline pair, depends on the growth histories of competing faults. In this case, subsidence of the hanging wall of the Balliolbreen fault would compete with uplift of the footwall of the Odellfjellet fault. Our observations suggest that the Balliolbreen fault became the dominant structure around Pyramiden during deposition of the fan complex, by linkage across splay faults to the Odellfjellet fault north of Pyramiden. Thereby, we suggest that the southern part of the Odellfjellet fault gradually became bypassed or dormant, which in the end would favor overall subsidence controlled by movements on the Balliolbreen fault. This transition may be evident in the lower Pyramiden fan complex. At an early stage, the fans abutting the buried small fault (Fault A, Fig. 14) indicate fairly small changes in the base level, with condensed and partly eroded sections in the up-folded sector towards the fault. No obvious changes in thickness can be seen to the east. The western thinning and onlap relationships and the repeated flooding events of these fans suggest that (fault-driven?) subsidence at times outpaced sediment influx. This caused episodic retreat of the fan lithofacies, before the fan reestablished, as mimicked by the cyclic stacking patterns. Similar geometries with sediment influx and progressive fault-driven folding of stacked fan deltas are well illustrated in the Suez rift, which also show punctuations by trangressive events (Gupta et al. 1999; Sharp et al. 2000).

The thicker fan higher in the fan complex of Pyramiden (lower fan in Fig. 14) shows a similar development as the fans below. However, at this stage the smaller fault A lower in the slope is bypassed, confirming its termination; and the fan has its apex near the Balliolbreen master fault. Furthermore, this fan shows significant thickening to the east, indicating that the relay folds have grown, and the Odellfjellet fault has become dormant. This is in accordance with the fault growth model argued for above. A similar pattern is depicted for the upper fan. Finally, as a through-going master fault came into place by breaching of the relay zone in this area, faulting became focused onto a single structure, and significant vertical movements could be expected. In the Pyramiden case, the entire alluvial fan complex of the former relay zone became flooded at this stage, and subsequently covered by marine carbonate deposits.

Billefjorden Trough basin model

The estimated maximum rift zone relief of 2-3000 meters for the Billefjorden Trough that developed during a period of nearly 50 mill. years suggests a slow average subsidence rate in the range of 5-6 m per 100.000 years. This would promote relatively low-energy depositional systems (excluding perhaps the situation of an axial river), as depicted by Johannessen and Steel (1992) for the centre of the Billefjorden Trough as well as many other basin centers (e.g. Gawthorpe and Leeder, 2000).

Reconstruction of the basin during deposition of the continental Hultberget Formation is tentative due to few good outcrops. However, the basin configuration would perceivably include gentle ridges above blind fault-tips as well as gentle overall subsidence of the future basin centre (Fig. 17A) - a pattern commonly observed in incipient rifts. Deposition is characterized by meandering rivers on broad flood plains towards coastal plains (Dallmann 1999). Faulting became more pronounced during deposition of the lower Ebbadalen Formation, with faults building some relief on both sides of the basin. However, most of the subsidence occurred along the BFZ, where a monocline likely started to form, which caused gentle tilting of the basin floor both towards the east and west. Near the basin-margin monocline, subsidence mostly outpaced sediment input and resulting in a mild surface flexure rather than a sharp fault scarp. Broad tidal flats developed around limited marine incursions. During periods of reduced accommodation space creation rates, for instance when fault slip to propagation rates were low, alluvial fan complexes were allowed to propagate from the rift margins across the basin flats, isolating playas and filling in the shallow marine basins. Alternatively, the extensive propagation of fan complexes could have been triggered by amplified flash flooding events and thereby higher sediment input caused by a wetter climate.

In the subsequent stages of the upper Ebbadalen to the lower Minkinfjellet Formation times (Fig. 16C), distinct fault segments with pronounced monoclines developed. Relief created by footwall flexural rebound controlled the drainage of the catchment areas, which experienced erosion and incision behind and around the anticlinal hinge of the monoclines. Subsidence became more localized and the earlier, wider basin realm more exposed and eroded. The overall picture is that of enhancement of distinct drainage patterns, focusing the clastic sediment input to certain areas, as reflected in the basin centre by a dominance of fine grained deposits (FA4). Exceptions are found in the areas of alluvial fans.

As the Odellfjellet and Balliolbreen fault segments linked to become a through-going fault (Fig. 17D), the locus of maximum subsidence (i.e. of accommodation space creation) located in the southwest, near a former relay zone around Pyramiden. Notably, at this stage marine flooding reached the master fault as the basin floor was gently tilted to the west. Both observations suggest that the western monocline was finally breached by a major fault scarp, as fault slip took over from folding. The basin experienced deeper marine deposits near the BFZ and gradually shallower marine conditions towards an eastern coastline, with clastic input arrested in estuaries along the basin margins. The following upper Minkinfjellet Formation succession hints at reduced fault-driven subsidence, with basin characteristics reverting to those prevalent during deposition of the lower Ebbadalen Formation. This change is consistent with a general regression. At the same time, the clastic input was redirected from the Pyramiden fan to the Sveenbrehøgda fan.

By Wordiekammen Formation times, the basin flanks were submerged and experienced open marine carbonate deposition (Pickard et al. 1996). Rift basin models predict thermal relaxation late in rift evolution and related widely distributed subsidence, or sagging (e.g., Cloetingh and Kooi 1992, Sales 1992, Gabrielsen et al. 2001, Cloetingh et al. 2008), which could explain the widespread flooding of the region. An eustatic sea-level rise at this time could have added to the flooding of the region. The faults of the basin were mildly reactivated (Fig. 17E), as seen by the local monoclines for example along the Løvehovden fault, with onlapping Black Crag Beds (Maher and Braathen 2011). Similarly, the footwall sections near the BFZ show shallow marine carbonate reefs and build ups, compared to the carbonate muds of the basin center (Elvebakk and Stemmerik, pers. comm. 2008). This faulting could have been thermally driven, or controlled by differential compaction of the basin fill. Compaction and removal by dissolution could also explain the Petuniabukta syncline (Fig. 6A), although the relief at the base of this unit exceeds 800 m, hinting at tectonics as an important cause for localized thickening (Maher and Braathen, 2011).

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